The latest Higgs results at CMS

HPNP2023, Osaka University

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On behalf of the CMS collaboration

2023-06-05

北京大學
PEKING UNIVERSITY

The LHC


LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

The CMS experiment

The Higgs boson

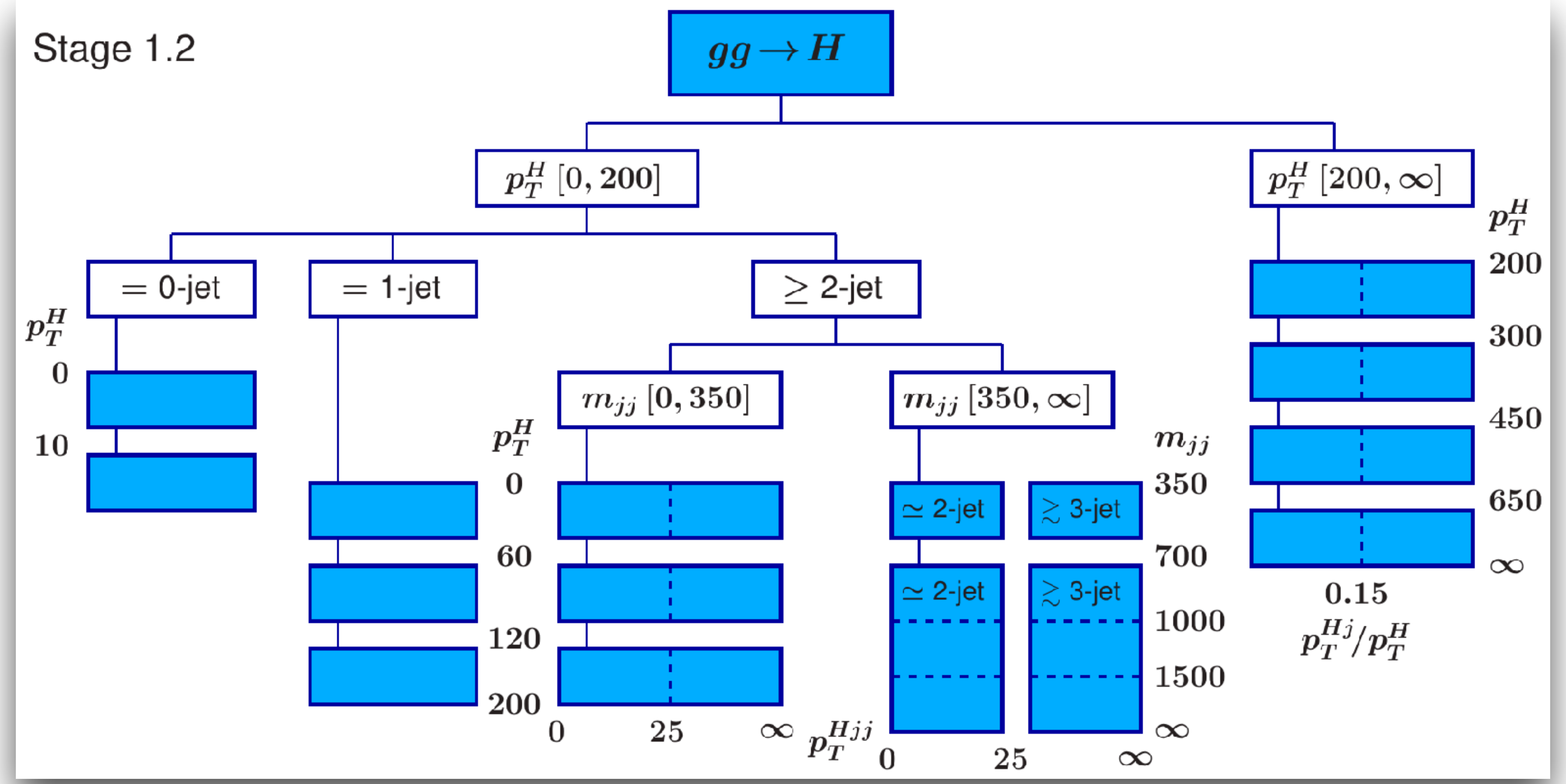
- The Higgs boson is at the center of the Standard Model and can also serve as a bridge to Beyond-the-Standard-Model physics
  - Stability of the universe, “portal” to dark matter, CP violation etc.
- It has been a decade after the discovery, and the profile of the Higgs boson becomes more clearer
- This talk will cover the latest Higgs measurements by CMS on this non-exhaustive list
  - Cross-section and couplings
  - Mass and width
  - Rare and exotic decays

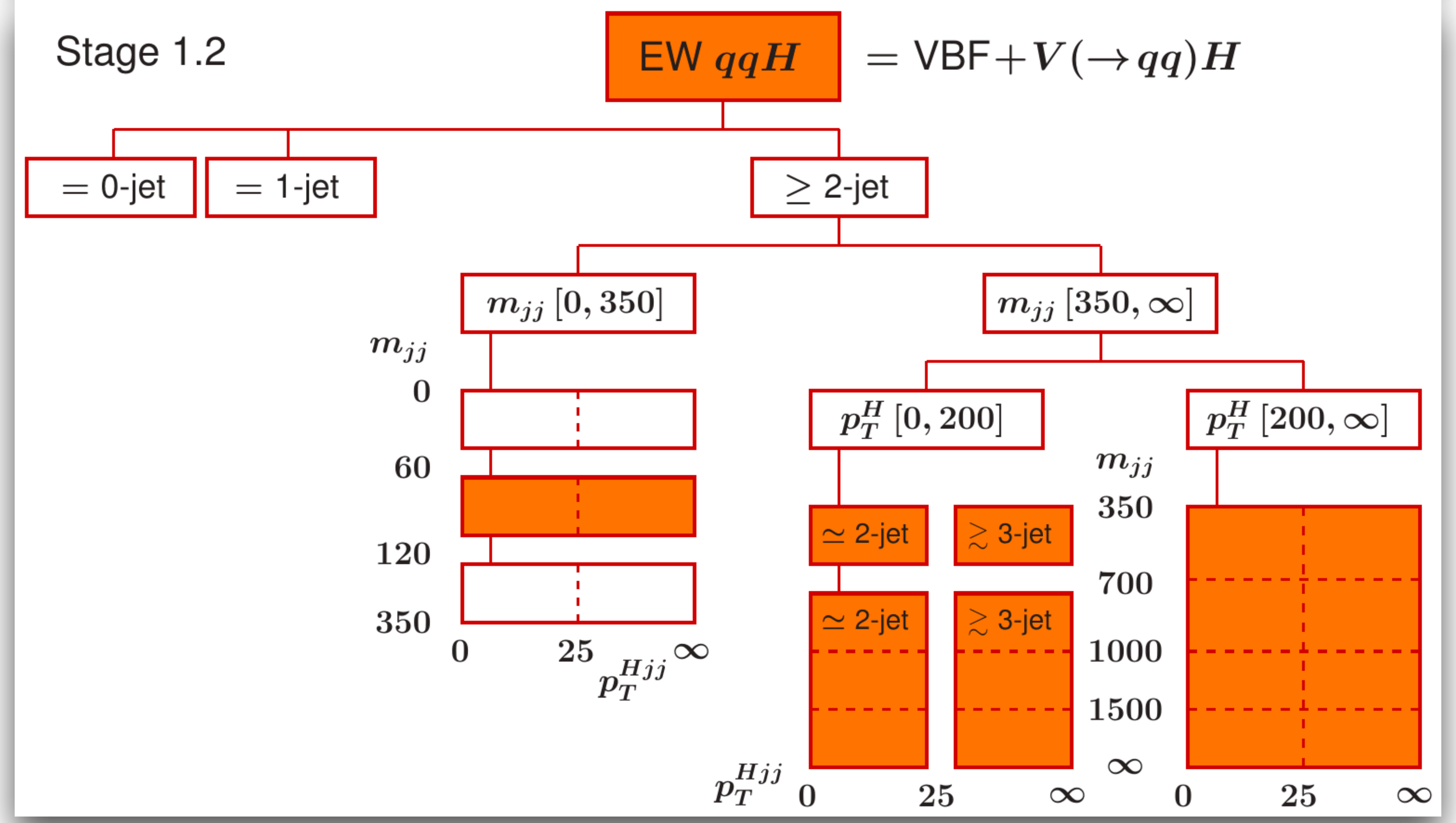
The productions and decays in SM

The productions and decays in SM

STXS

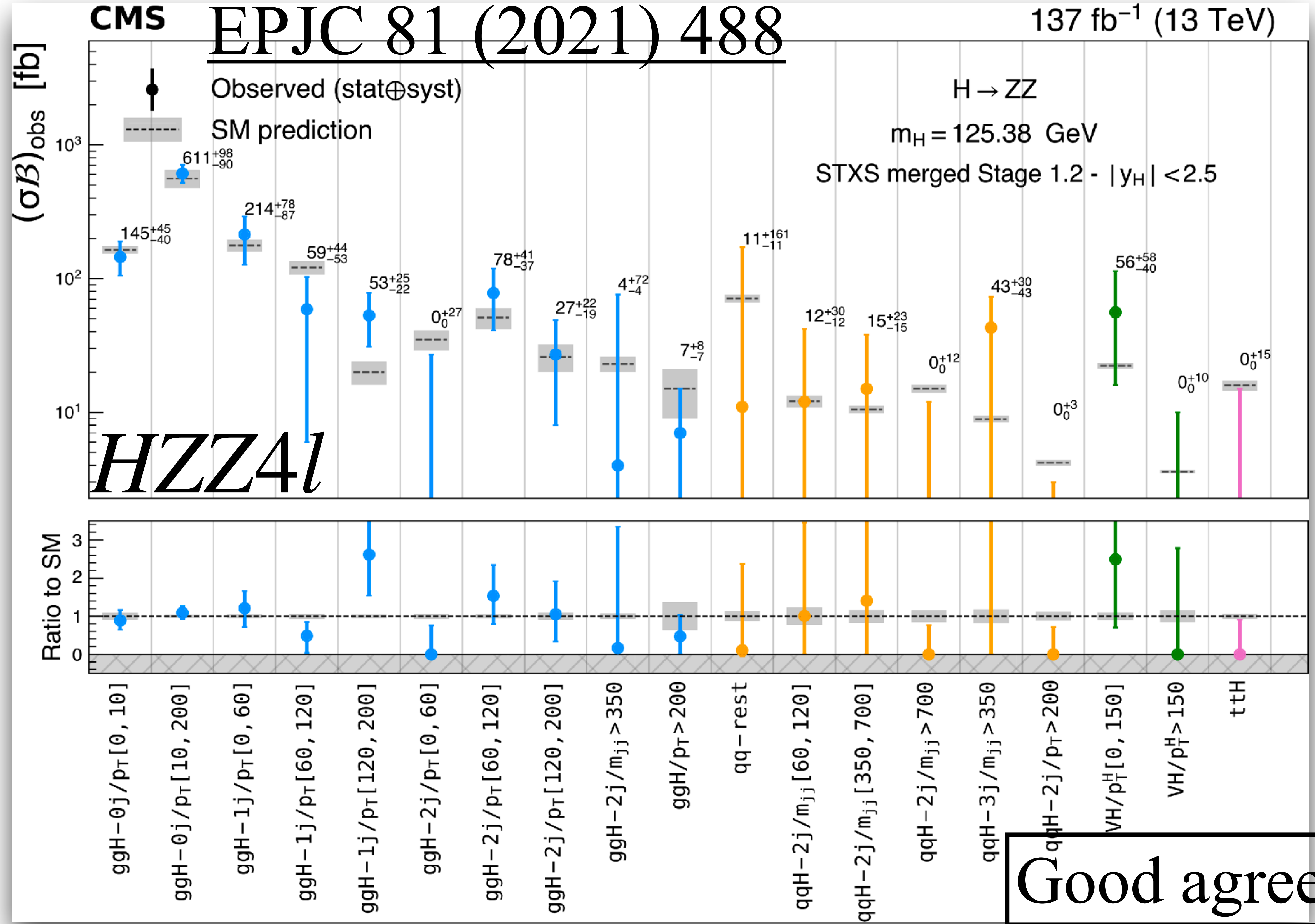
- The Simplified Template Cross Section (STXS) provides a pragmatic interface from the experimental accessibility to the theoretical handlers on SM and BSM phenomena, by using coarse kinematic bins
  - Balancing the experimental sensitivity (XS measurements with maximum sensitivities with deeply optimized cuts) and the model independence (differential XS measurements with fine kinematic bins using simple cuts)
- The experiments are reaching the precision for measuring STXS in Stage 1.2

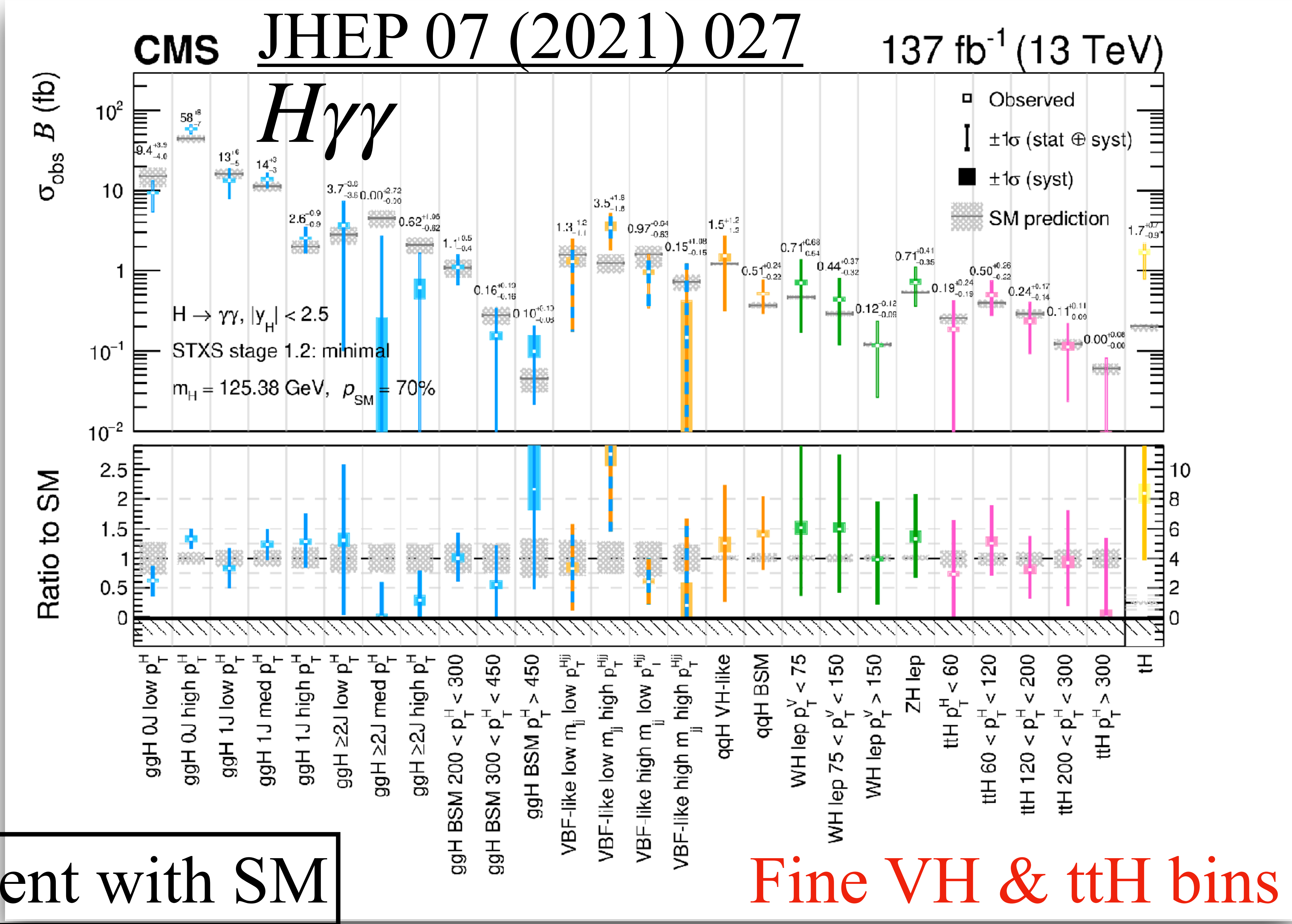




STXS in the "golden" channels

- *HZZ4l*, small BR, but high S/B, full m_H reconstruction with high resolution: matrix element information for categorization and m_{4l} for fits, providing merged STXS Stage 1.2 measurements
- *Hγγ*, small BR, excellent mass resolution: BDT and cuts for categorization and $m_{\gamma\gamma}$ for fits, providing slightly merged STXS Stage 1.2 measurements



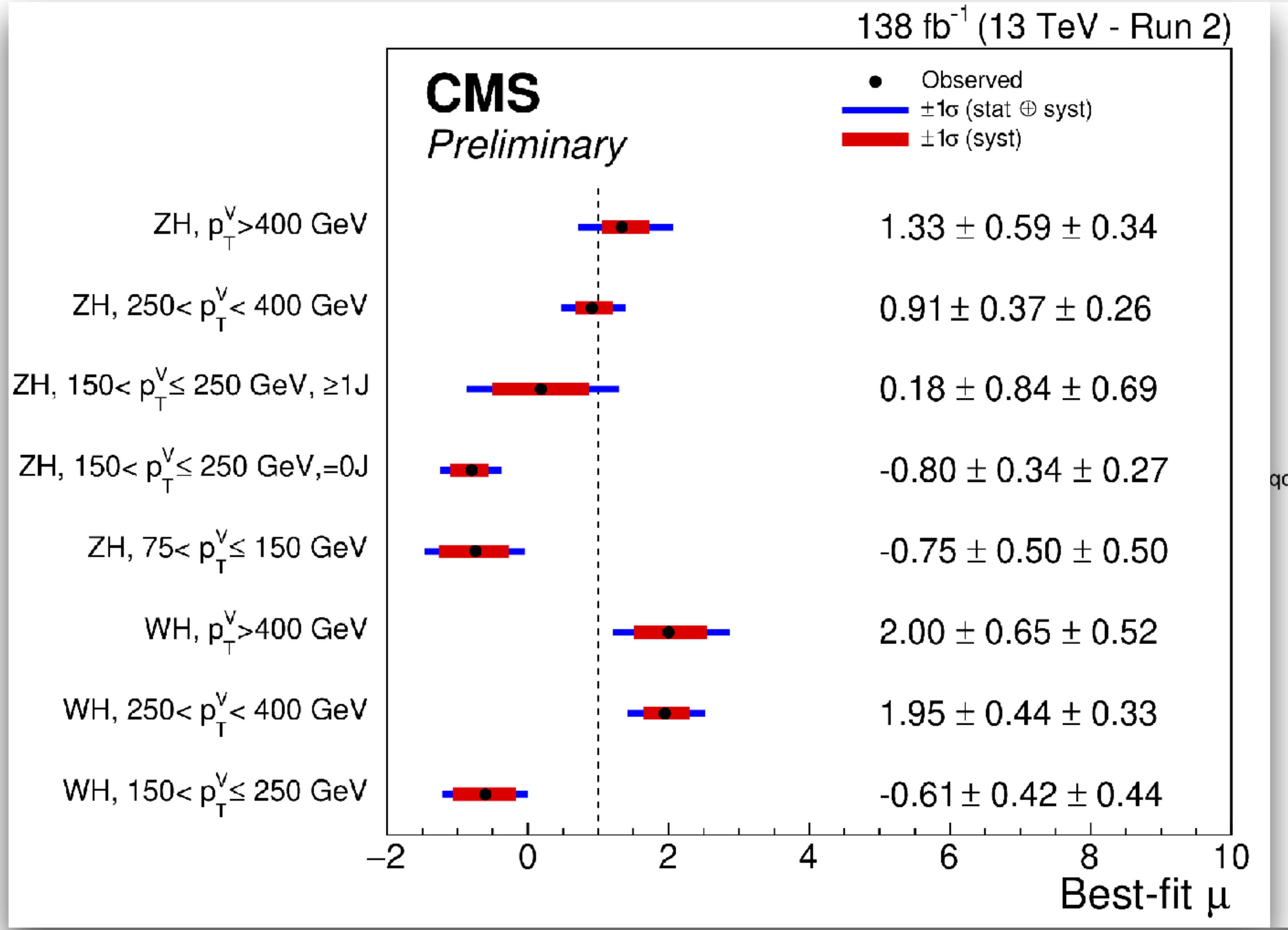


Good agreement with SM

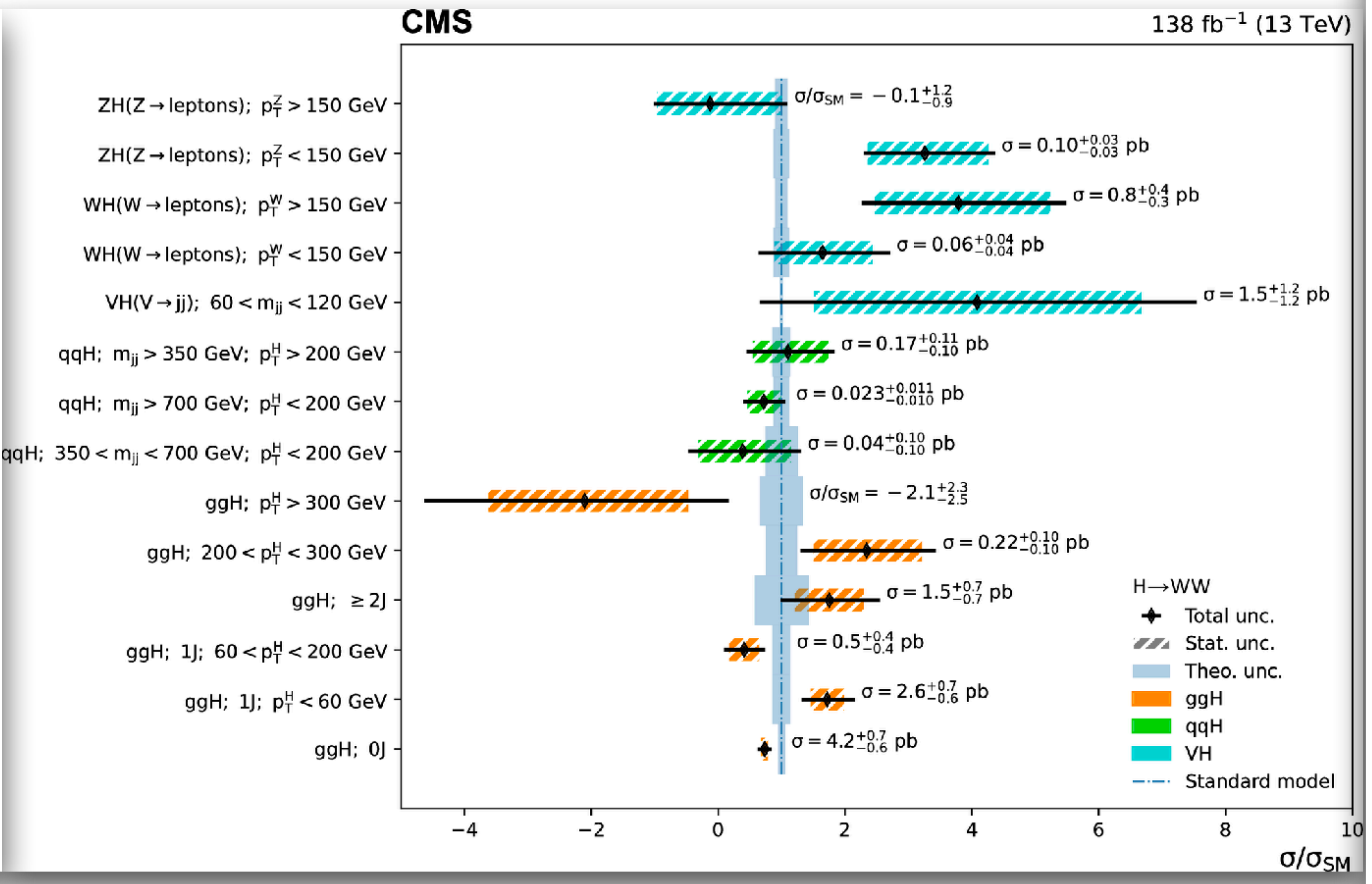
Fine VH & ttH bins

STXS in high-stats channels

- High-stats channels including *Hbb*, *HWW* and *Hττ* provide additional sensitivities in STXS
- The focuses are mainly on ggH, qqH and V(lep)H

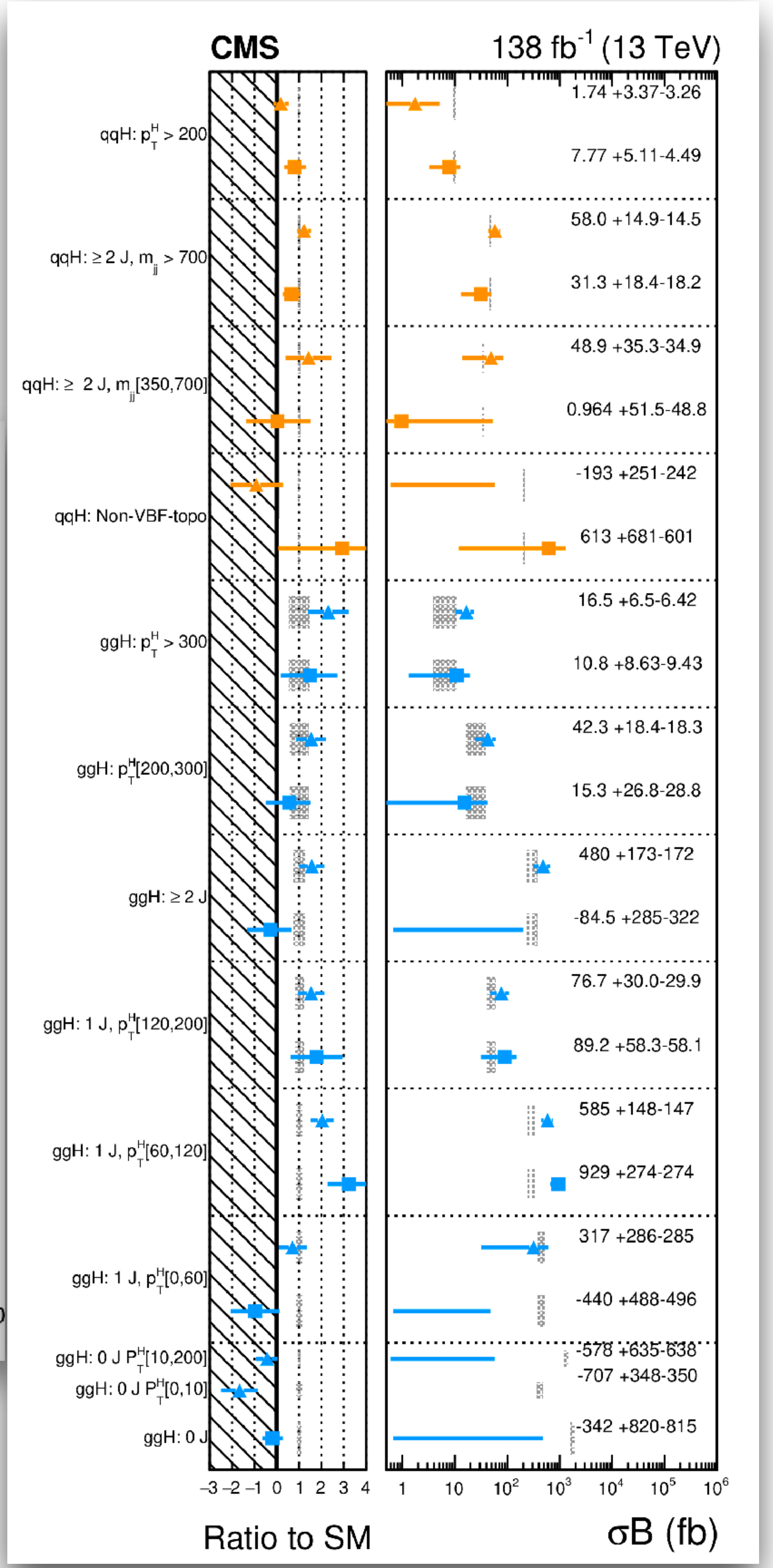


Hbb focuses on V(lep)H
CMS-PAS-HIG-20-001



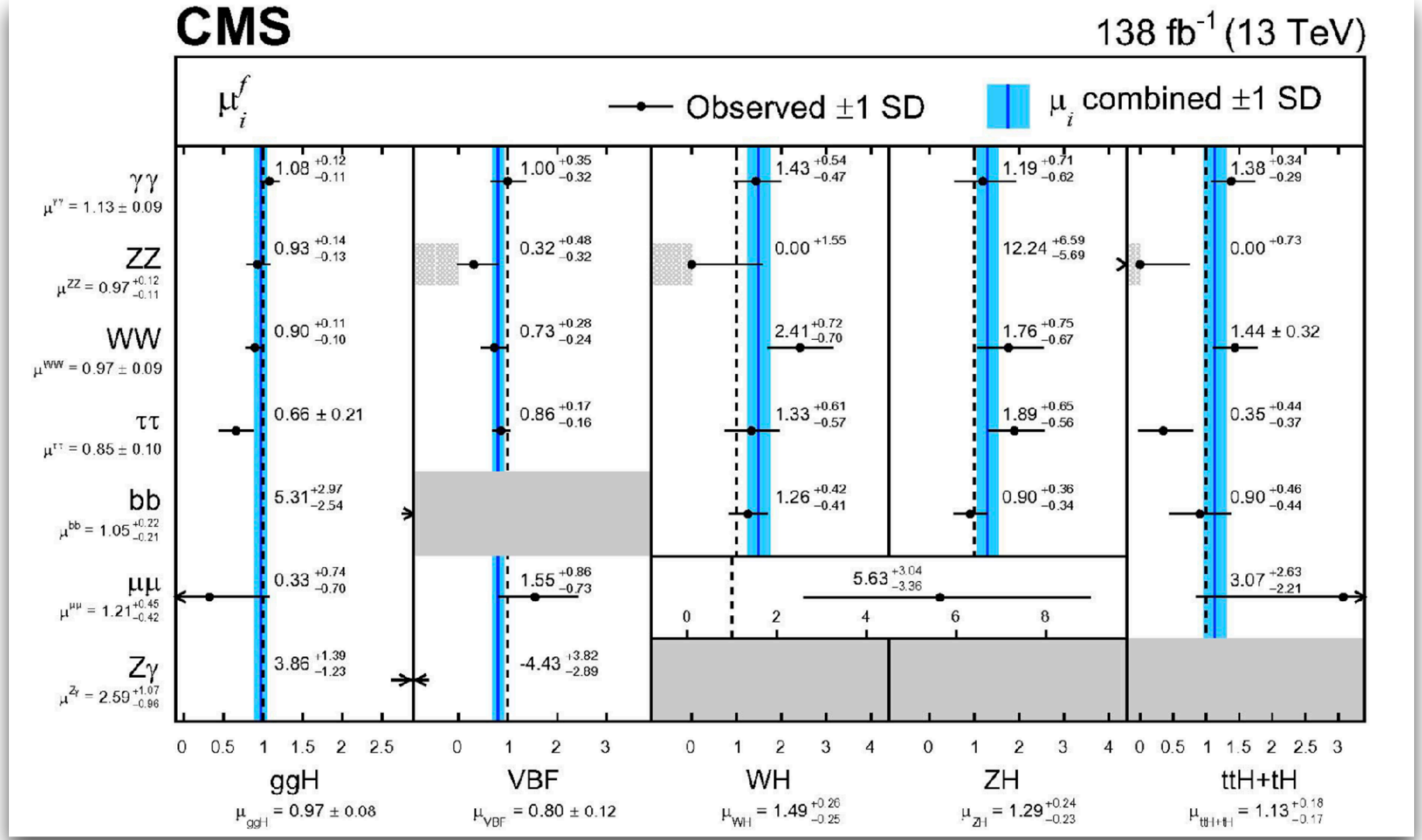
HWW on ggH, qqH and V(lep)H
Accepted by Eur. Phys. J. C

Hττ focuses on ggH and qqH
Accepted by Eur. Phys. J. C



The combination

- At the 10th anniversary of the Higgs discovery, the “portrait” of the Higgs boson by CMS was published
  - A full combination of available experimental observables
  - A deep examination of the Higgs mechanism
- Results include inclusive signal strength μ, and a full breakdown from various couplings in the κ framework
- A good agreement with SM is observed at the current precision

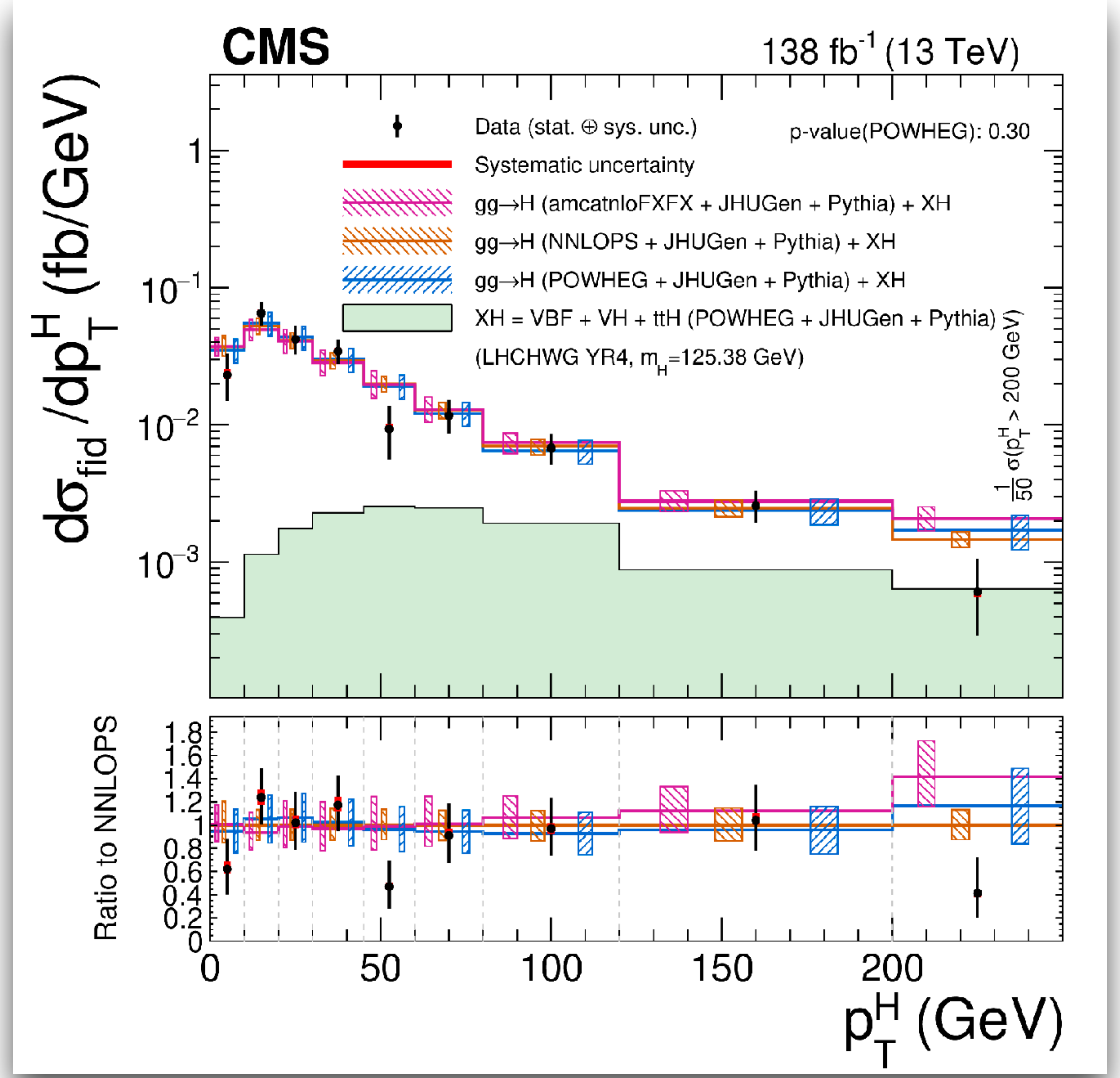


The signal strength μ’s

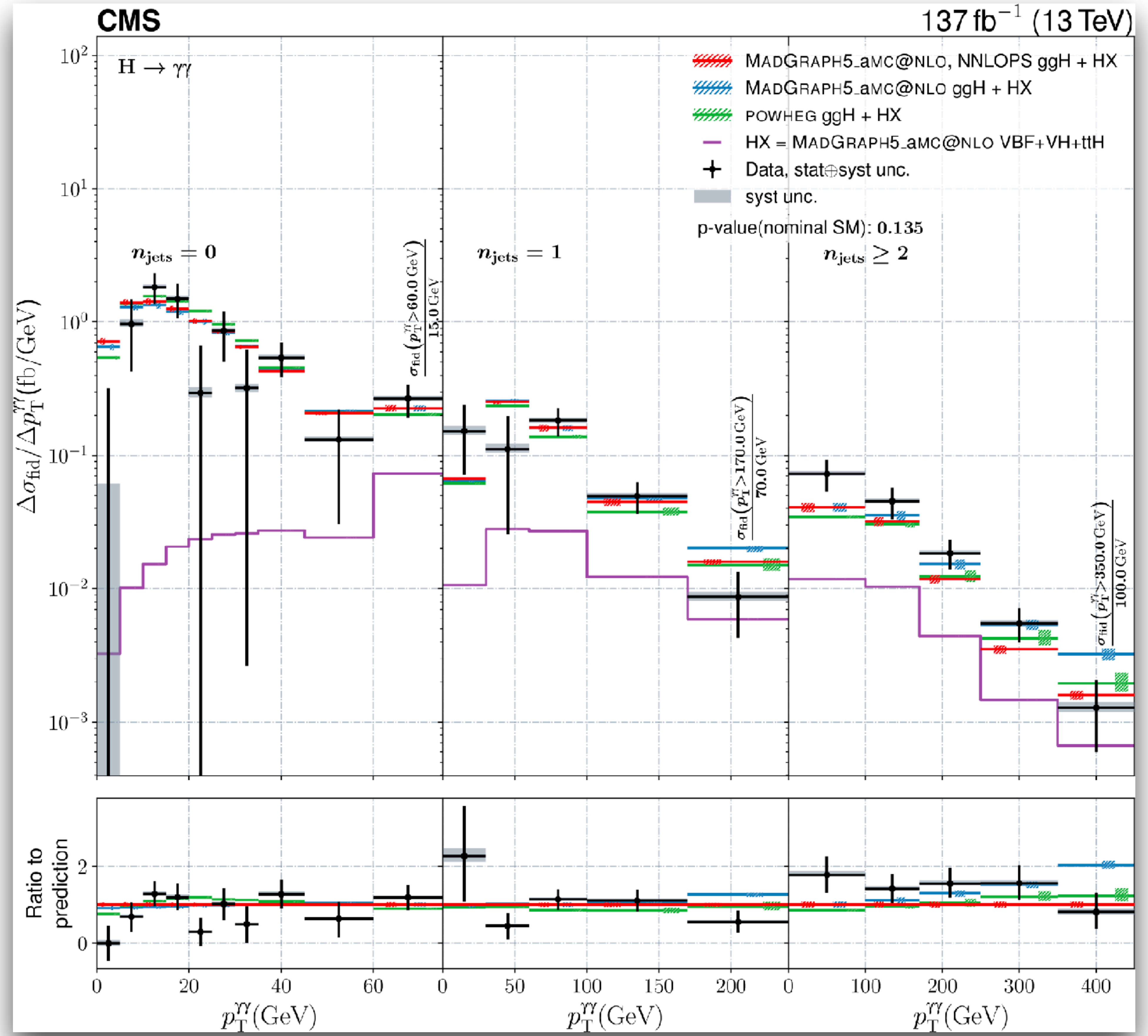
Nature 607 (2022) 60-68

Differential XS

- Largely from *HZZ4l* and *Hγγ*
- Provide a big variety of unfolded kinematics with model independence



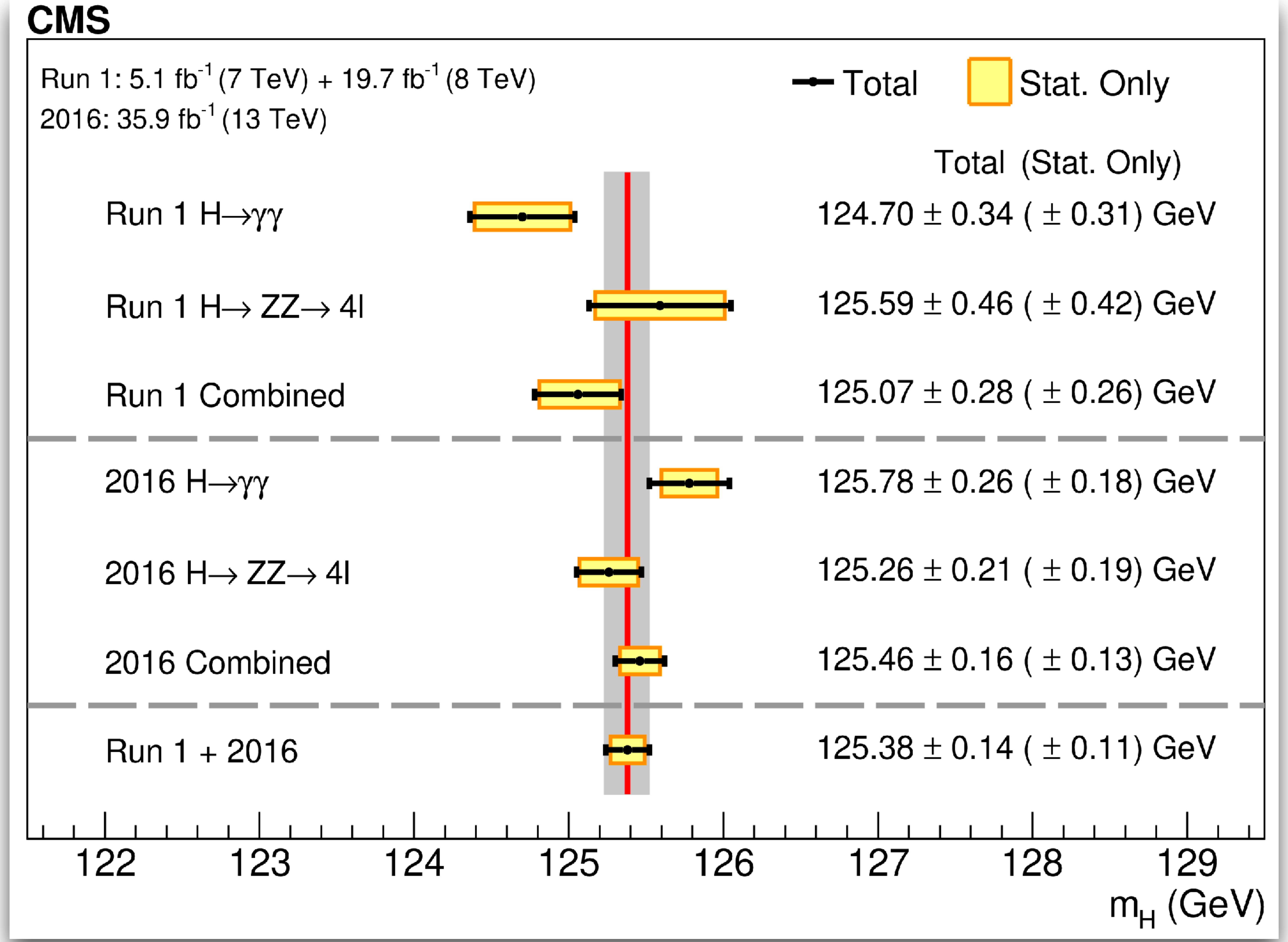
HZZ4l Submiited to JHEP



Hγγ Accepted by JHEP

The Higgs mass

- The mass is essential and determines many other properties (XS, BR etc.)
- Largely rely on *HZZ4l* and $H\gamma\gamma$ thanks to their complete reconstruction of the final state and their excellent mass resolution (1-2%)



<u>Run1 ATLAS+CMS:</u>

$m_H = 125.09 \pm 0.24$ GeV

Phys. Rev. Lett. 114 (2015) 191803

<u>Now CMS:</u>

$m_H = 125.38 \pm 0.14 \pm 0.11$ GeV

$H\gamma\gamma$ & *HZZ4l* with Run1+2016

<u>Phys. Lett. B 805 (2020) 135425</u>

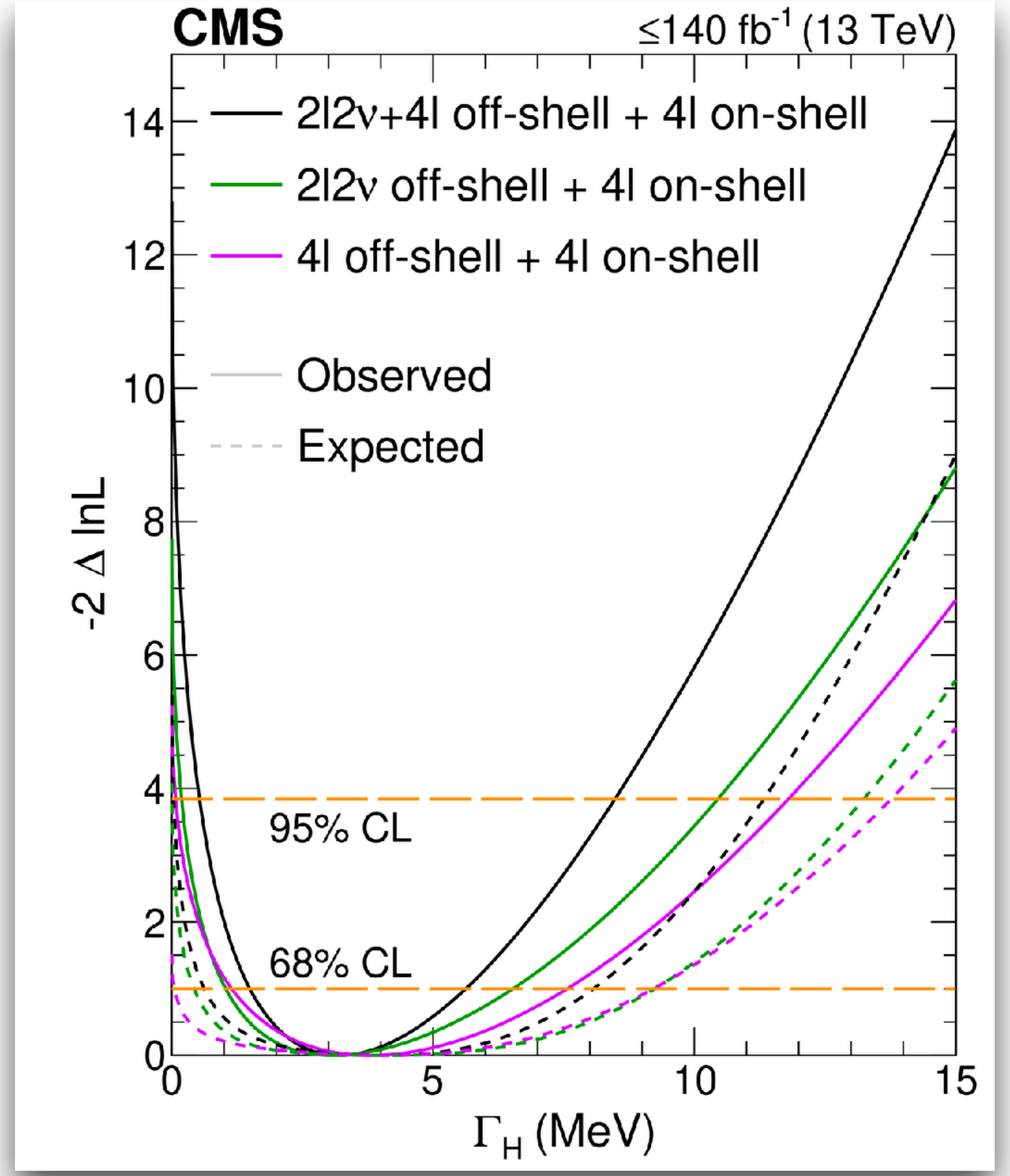
The Higgs width

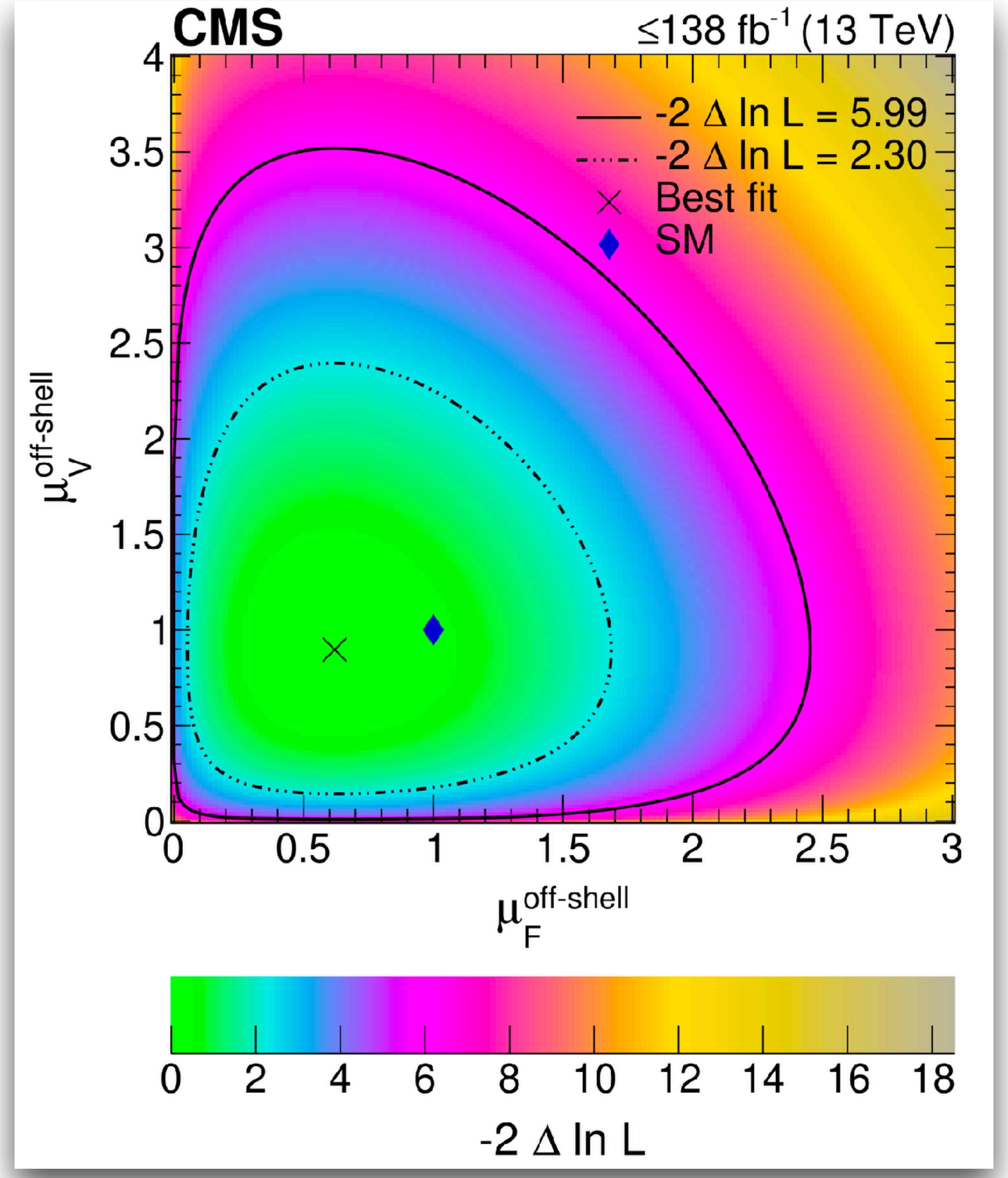
- Not quite possible to directly measure the width that is ~4.07 MeV, given the experimental resolution at ~O(1) GeV
- But can exploit the on-shell and off-shell production using *HZZ4l*

$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

$\Gamma = 3.2^{+2.4}_{-1.7}$ MeV

Nat. Phys. 18 (2022) 1329

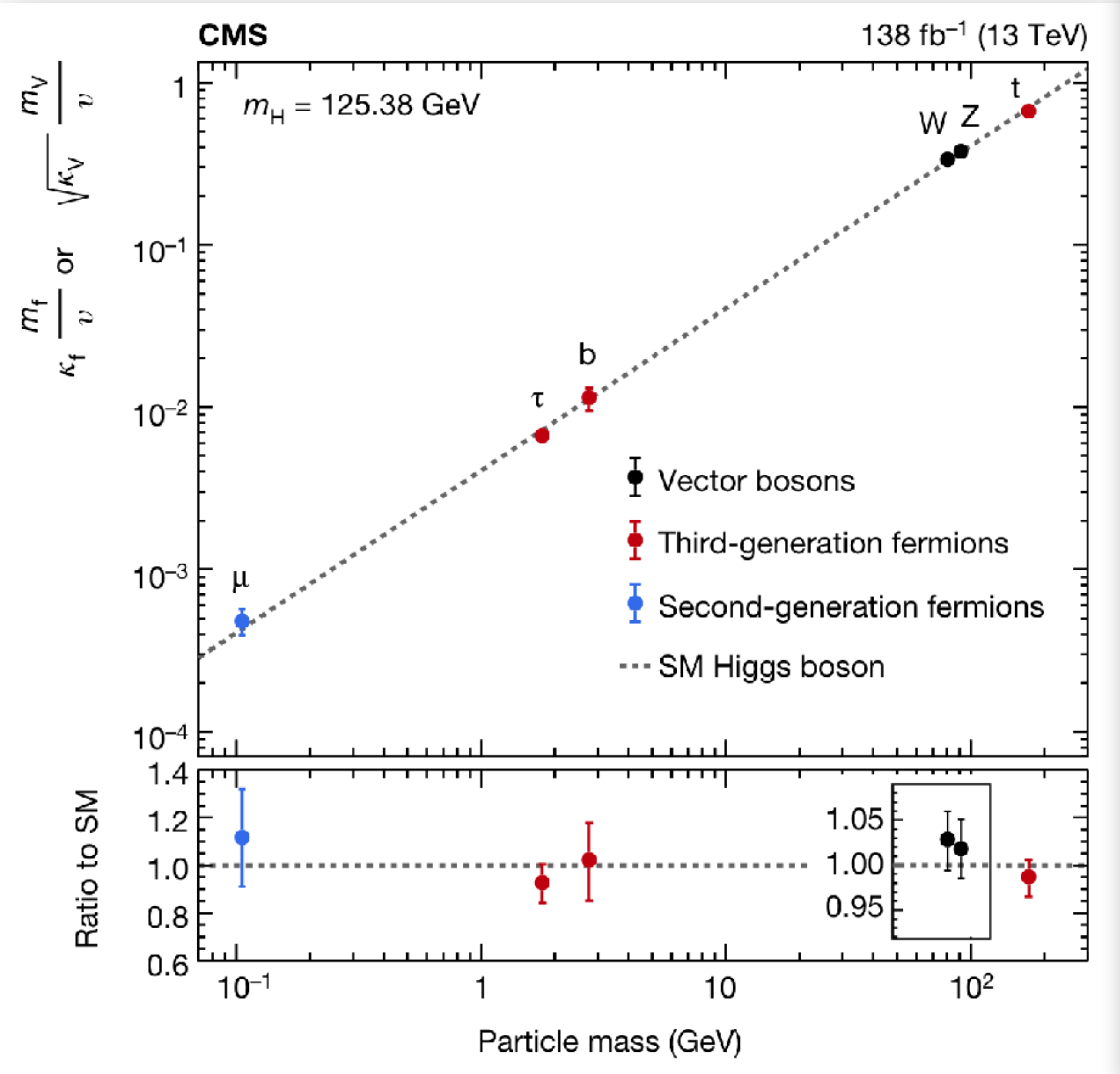


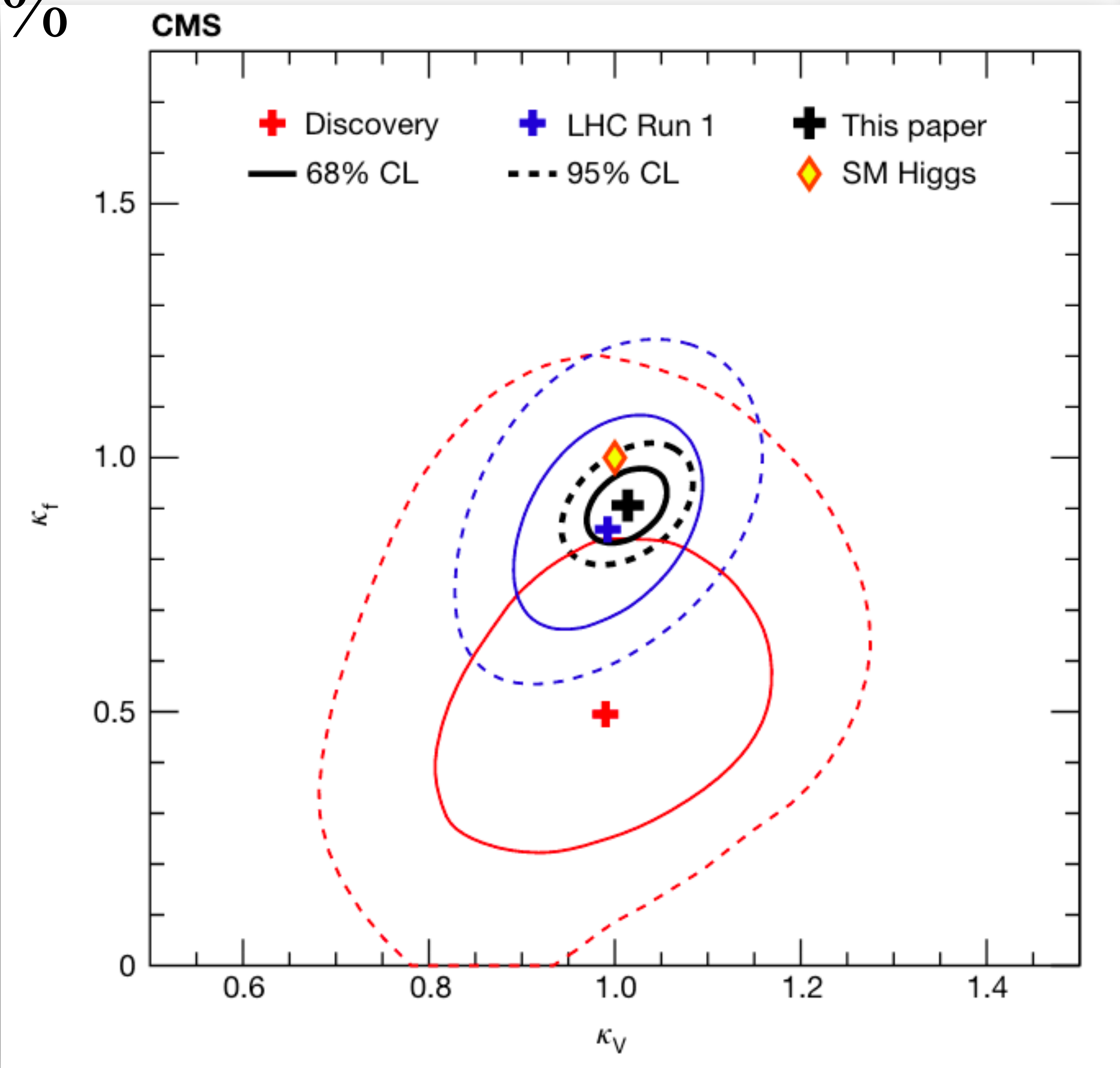


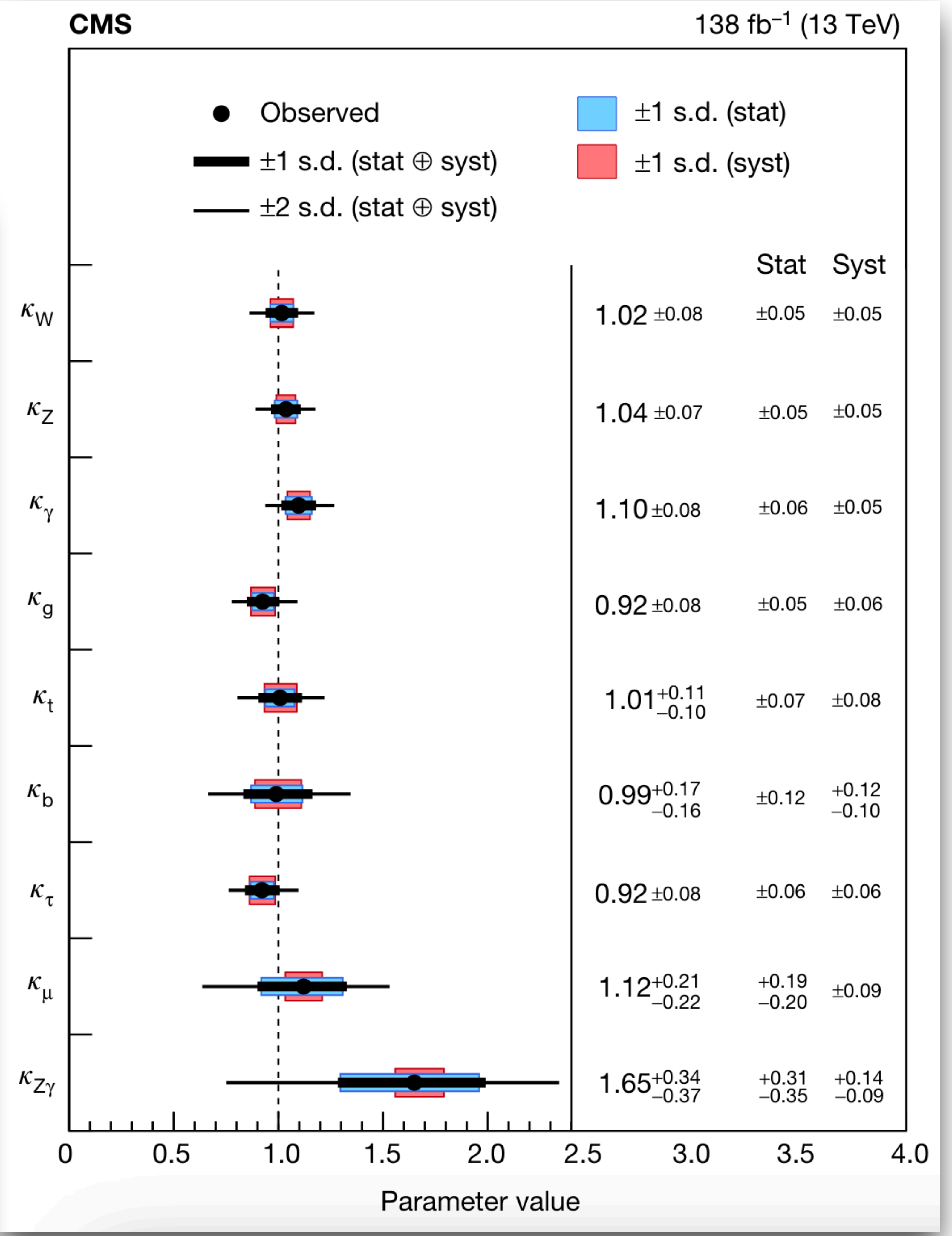
The couplings

Nature 607 (2022) 60-68

- The couplings measurements range over three orders of magnitude
- Couplings in the κ framework can be measured with a precision as good as < 10%

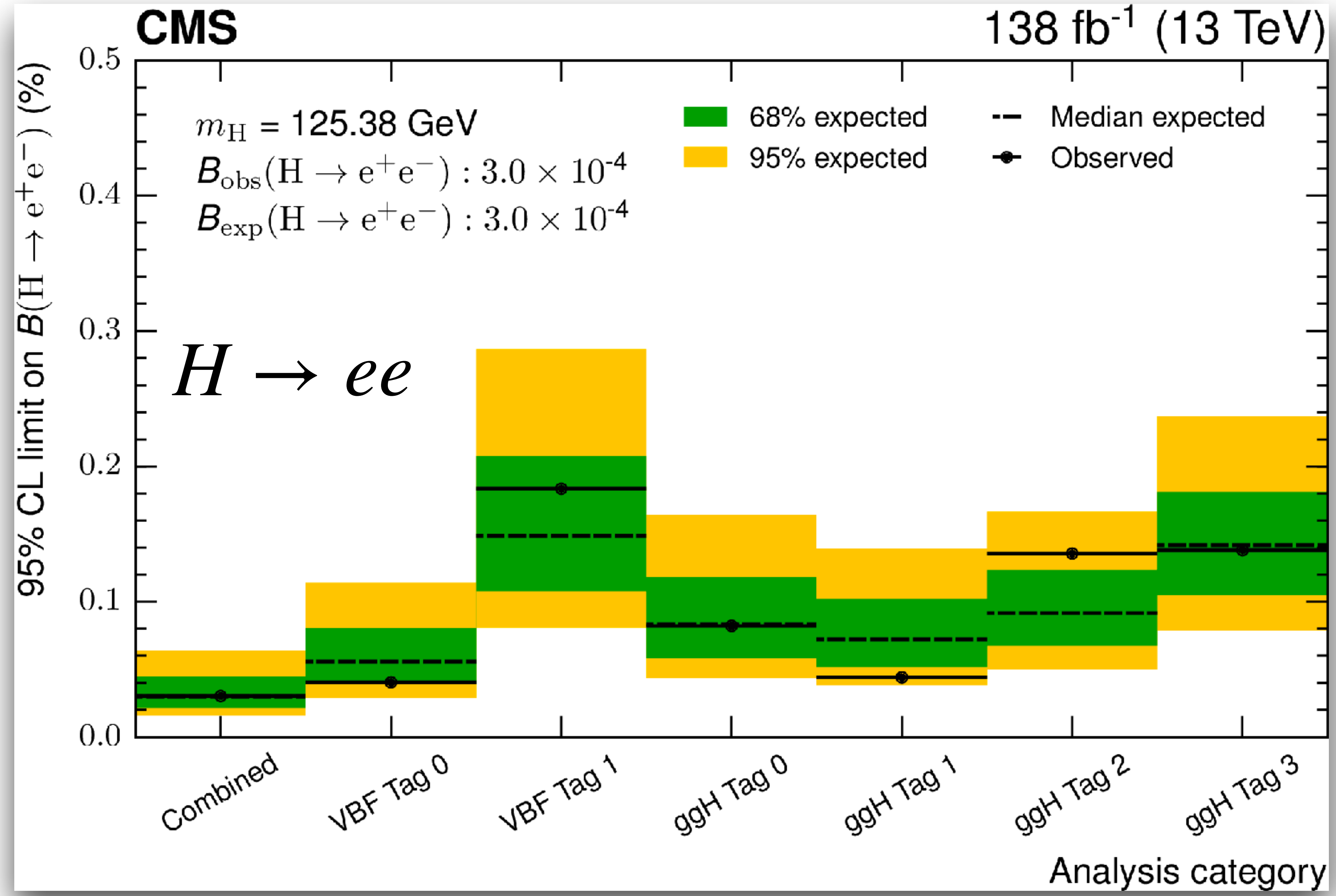


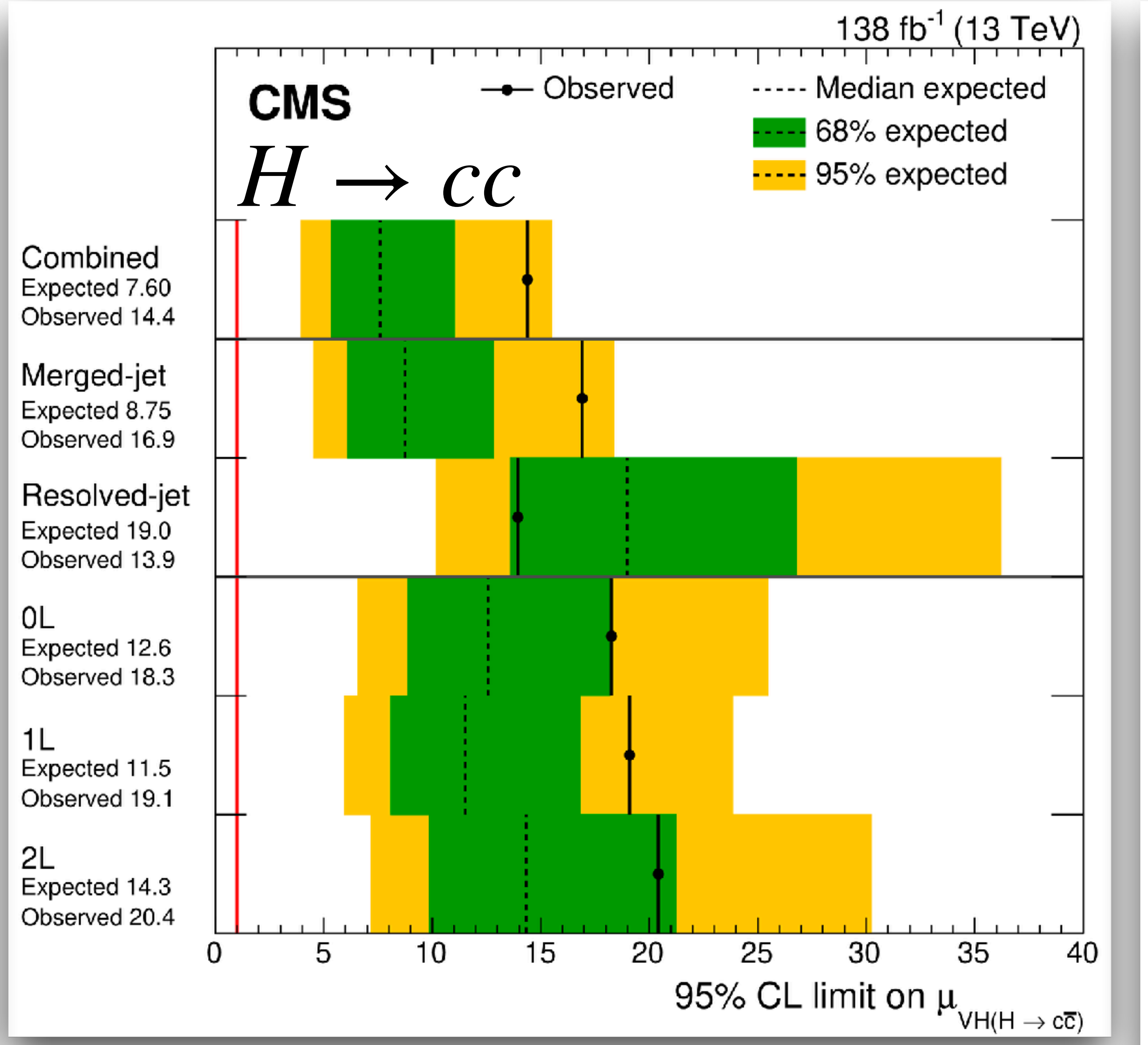


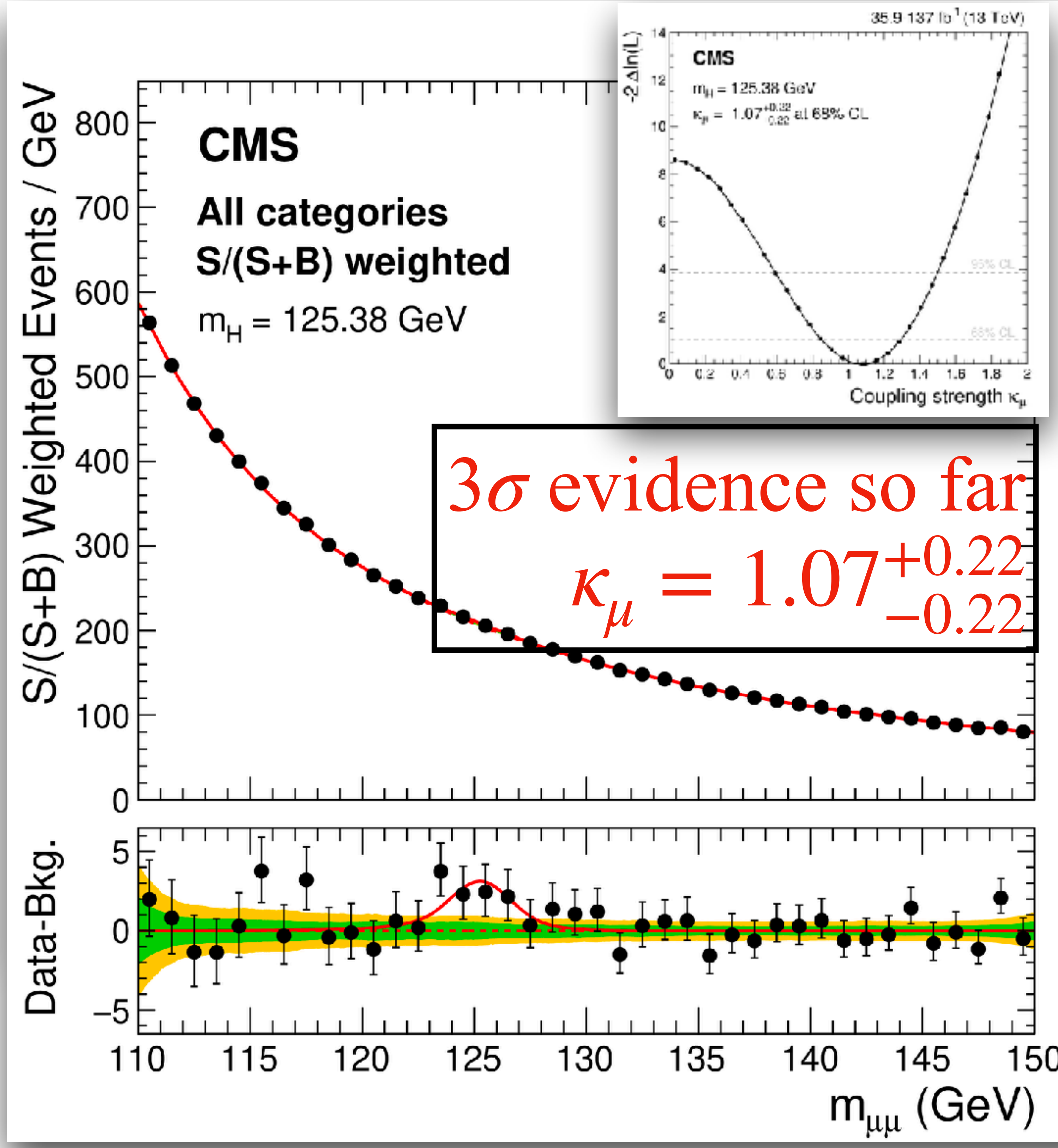


Couplings to lighter fermions

- Reaching out to the first and second generation fermions







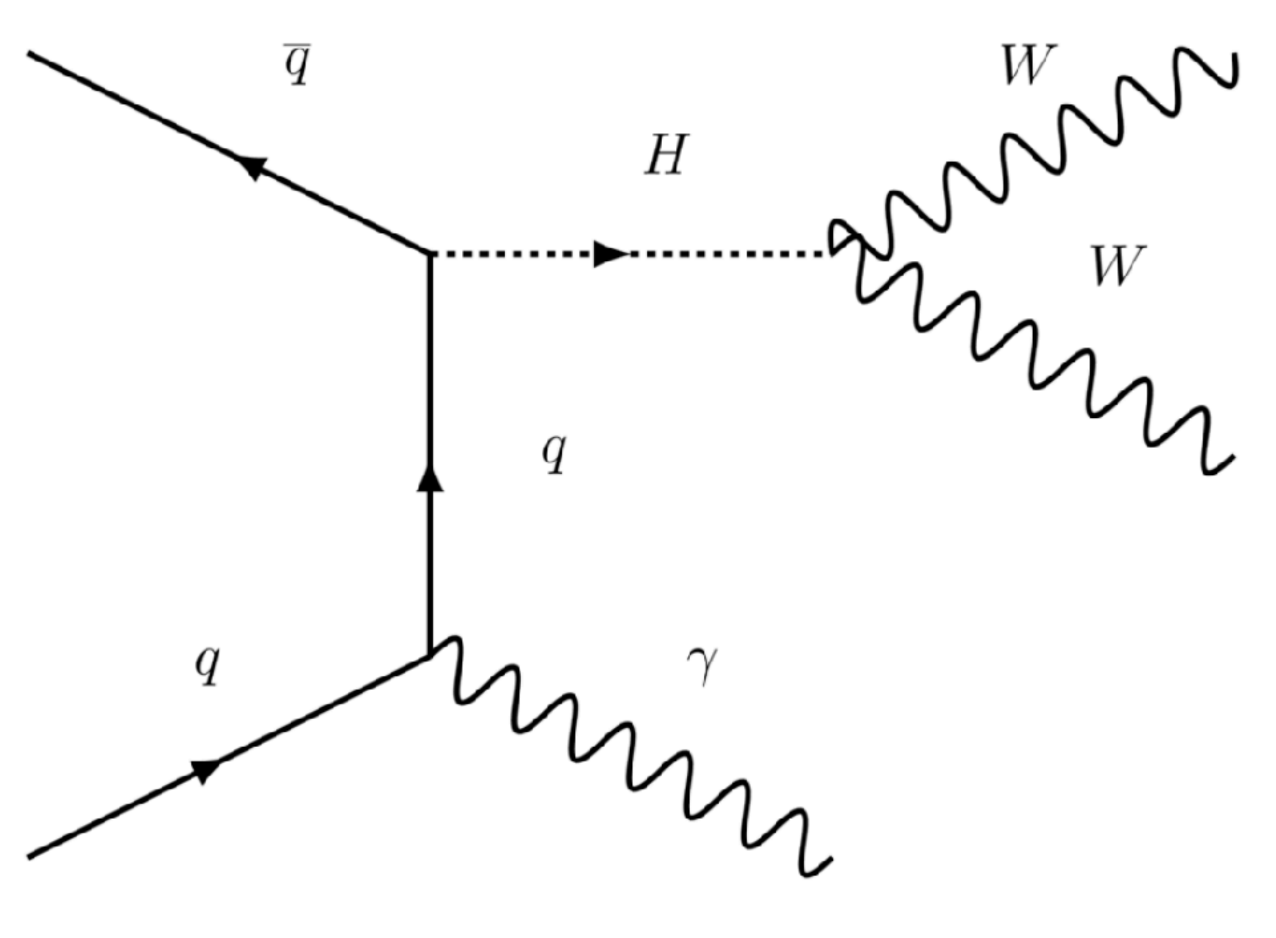
$BR(H \to ee) < 3.0 \times 10^{-4} (3.0 \times 10^{-4})$ at 95% CL. Accepted by PLB

$1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$) at 95% CL. Accepted by PRL

JHEP 01 (2021) 148

Couplings to lighter fermions

- A rare production of $pp \to \gamma H$ is probed with $H \to WW$ in the triple boson analysis of $WW\gamma$
- Particularly sensitive to u,d,c,s couplings
- Most stringent constraints on u,d to date



Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq$13000 (16000)
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq$14000 (17000)
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq$1300 (1700)
$c\bar{c} \to H + \gamma \to e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq$110(200)

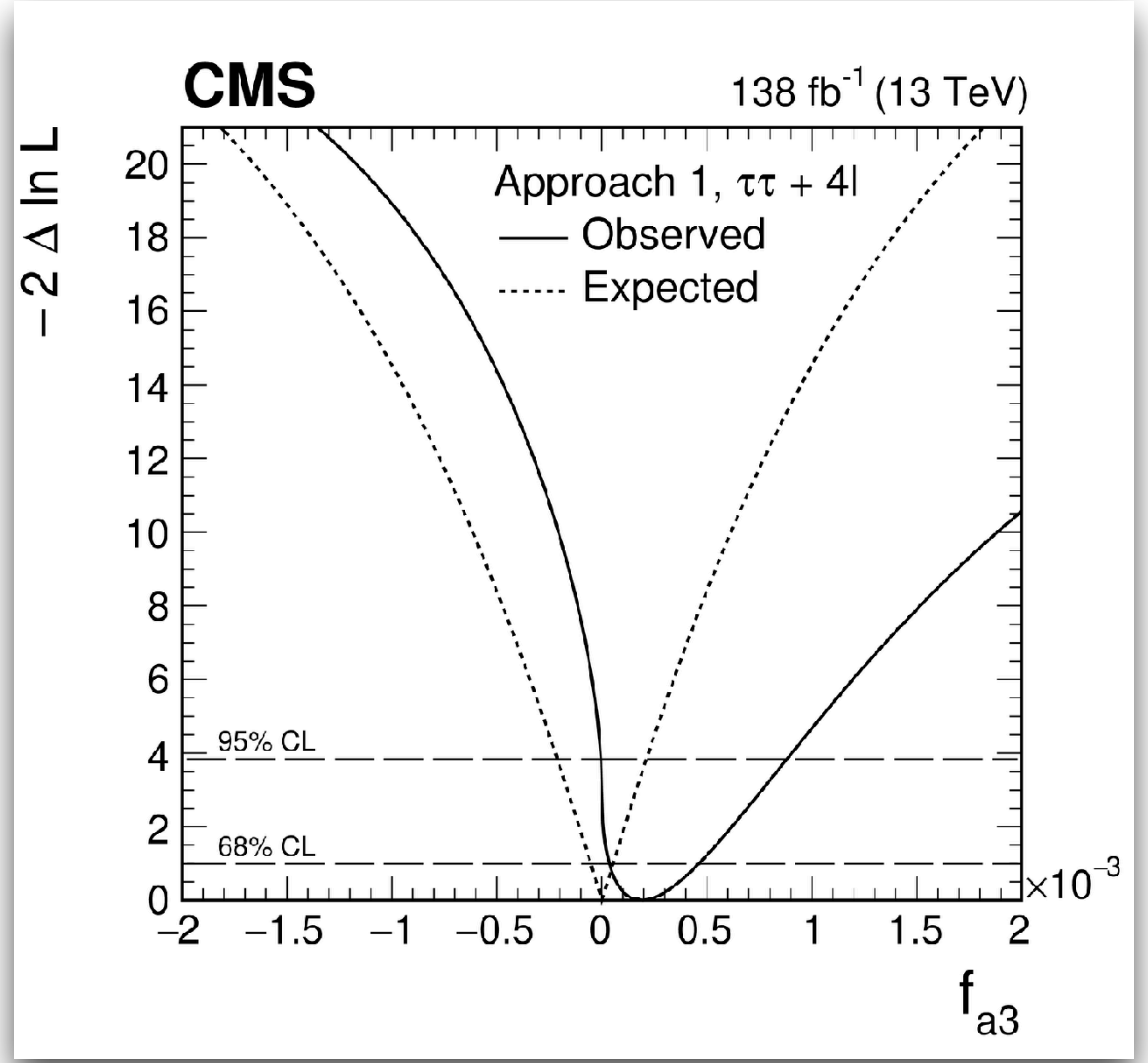
CMS-PAS-SMP-22-00

Anomalous couplings

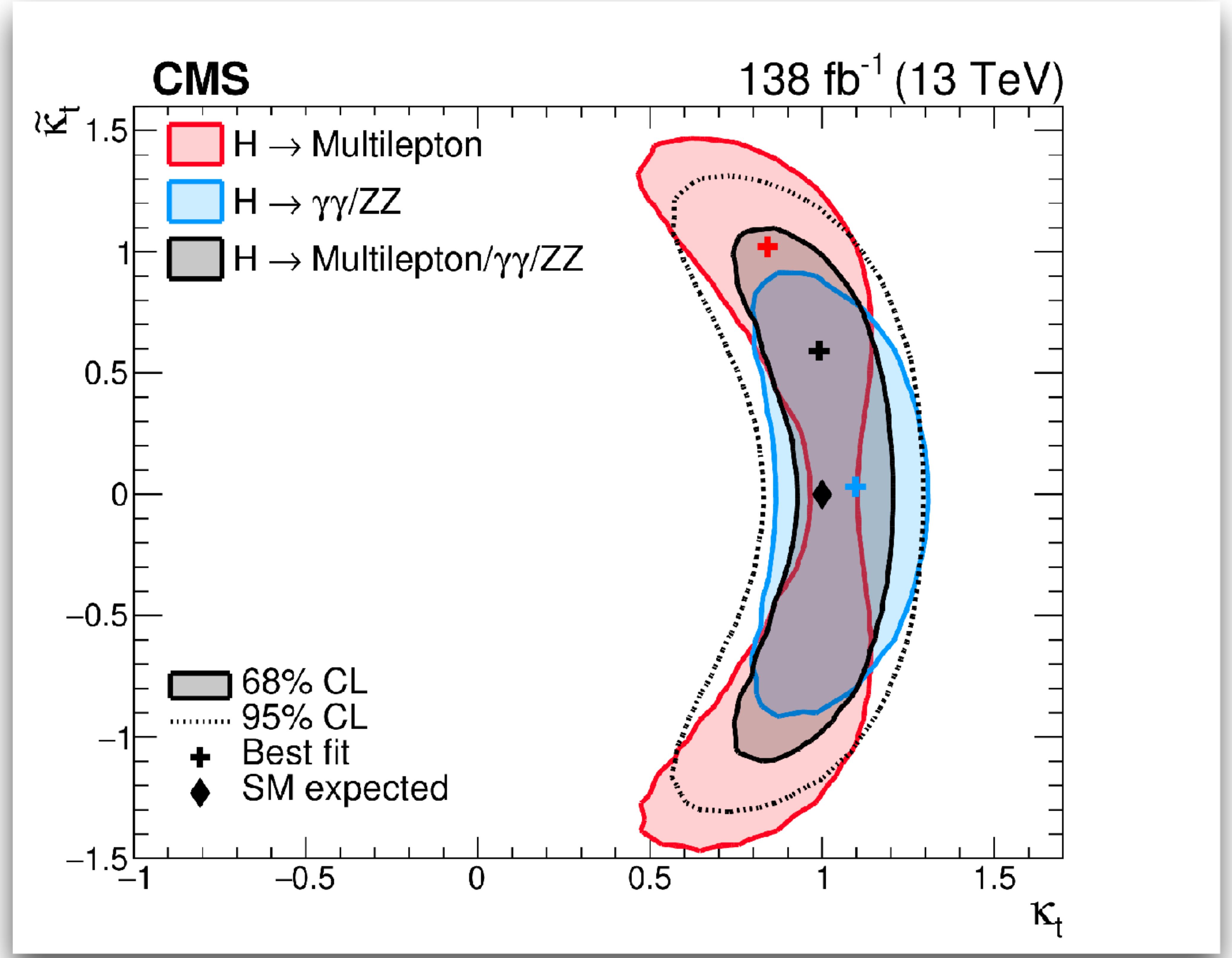
- The anomalous couplings are pushed to new frontiers

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

$$\mathcal{L}_{\mathrm{t\bar{t}H}} = \frac{m_{\mathrm{t}}}{v} \bar{\psi}_{\mathrm{t}} (\kappa_{\mathrm{t}} + i\gamma_5 \tilde{\kappa}_{\mathrm{t}}) \psi_{\mathrm{t}} \mathrm{H}$$



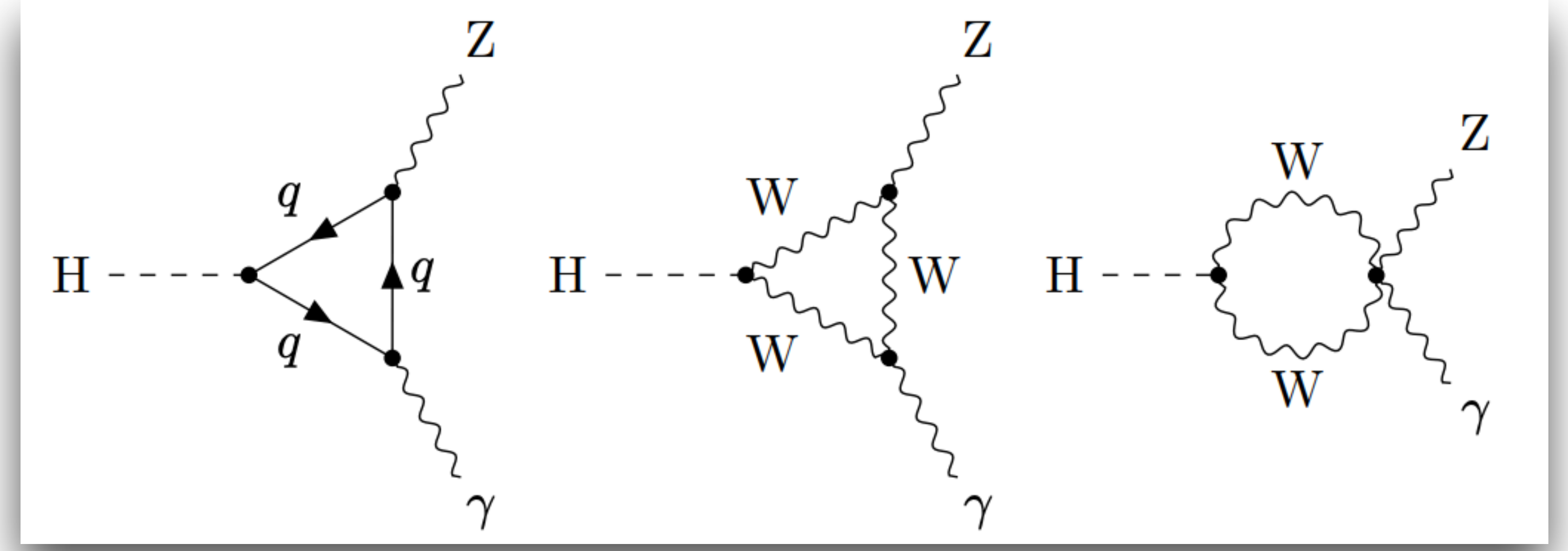
HZZ4l + *Hττ*. Accepted by PRD

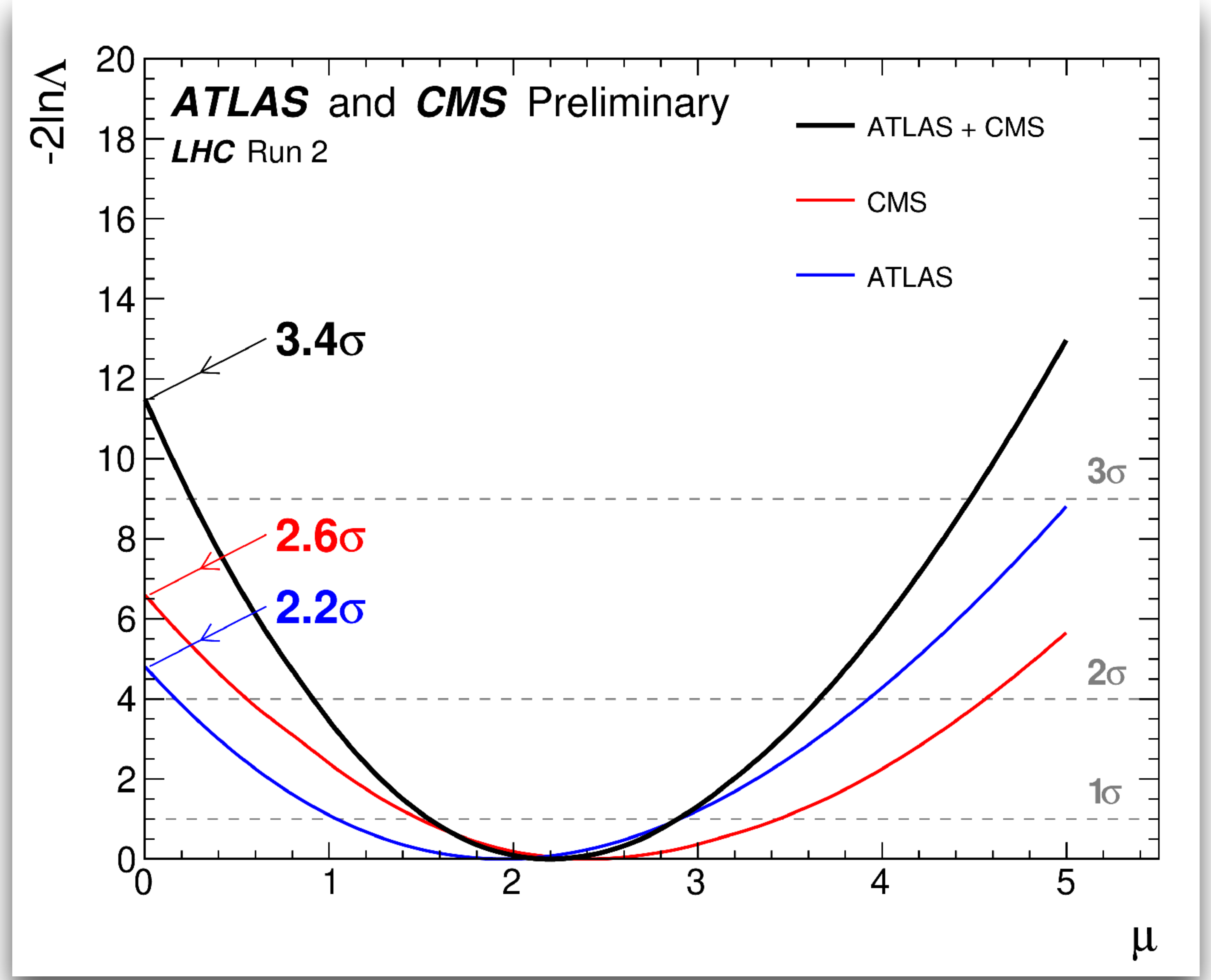


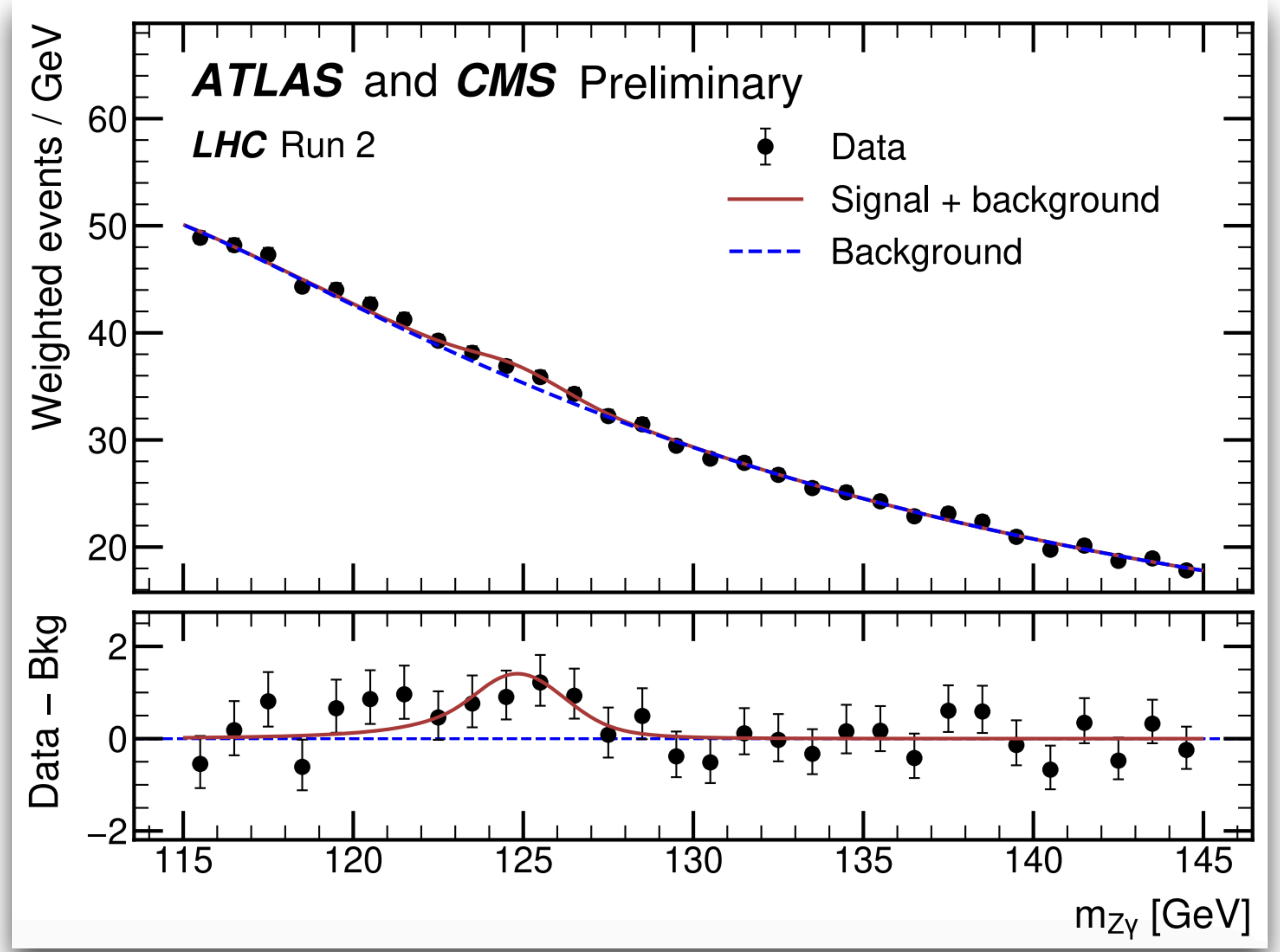
ttH: multilepton, *Hγγ*, *HZZ4l*. Accepted by JHEP

$H \to Z\gamma$

- $H \to Z\gamma$ with loop where new physics can hide
- ATLAS and CMS results are combined for 3.4σ







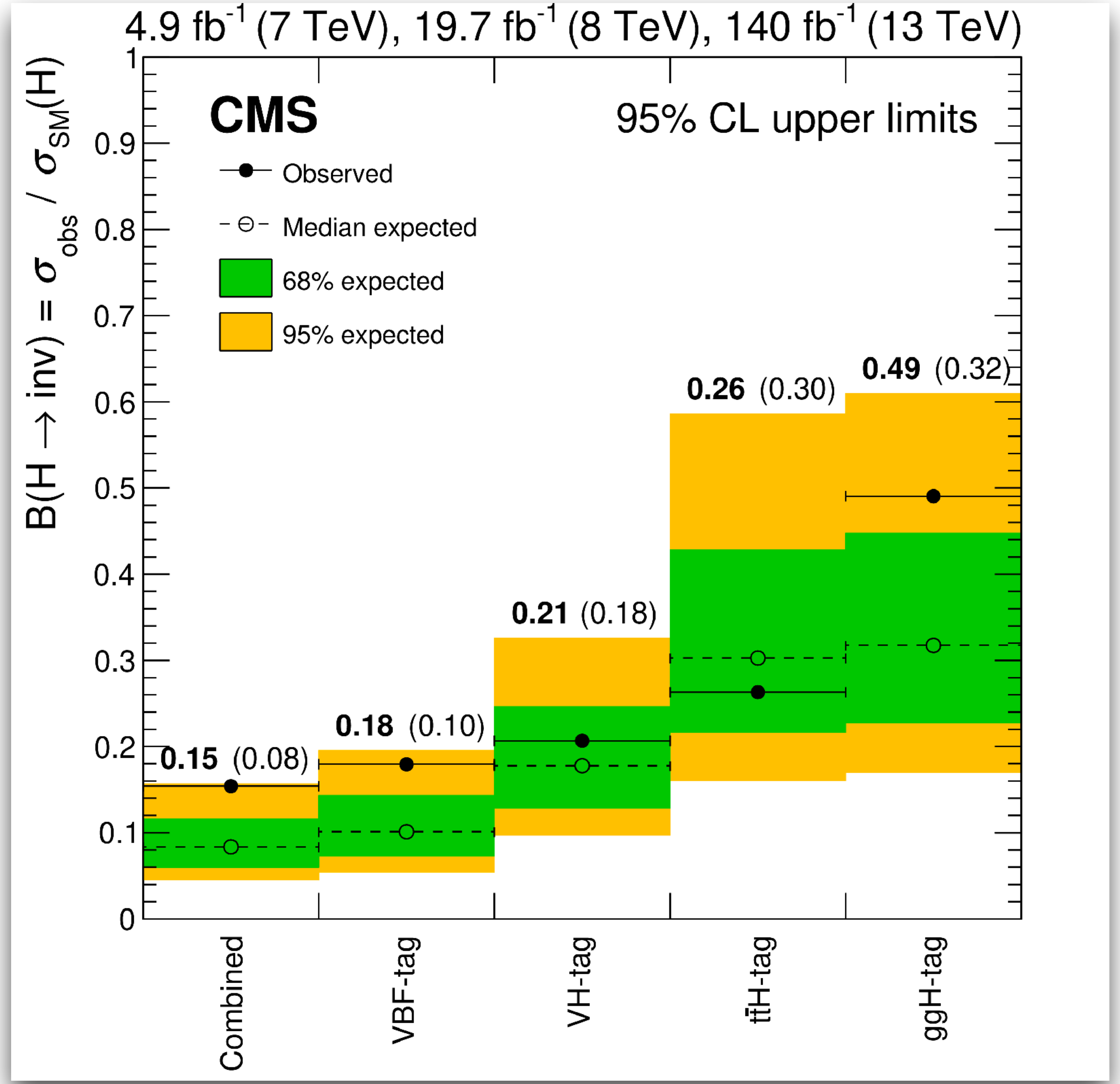
CMS-PAS-HIG-23-002

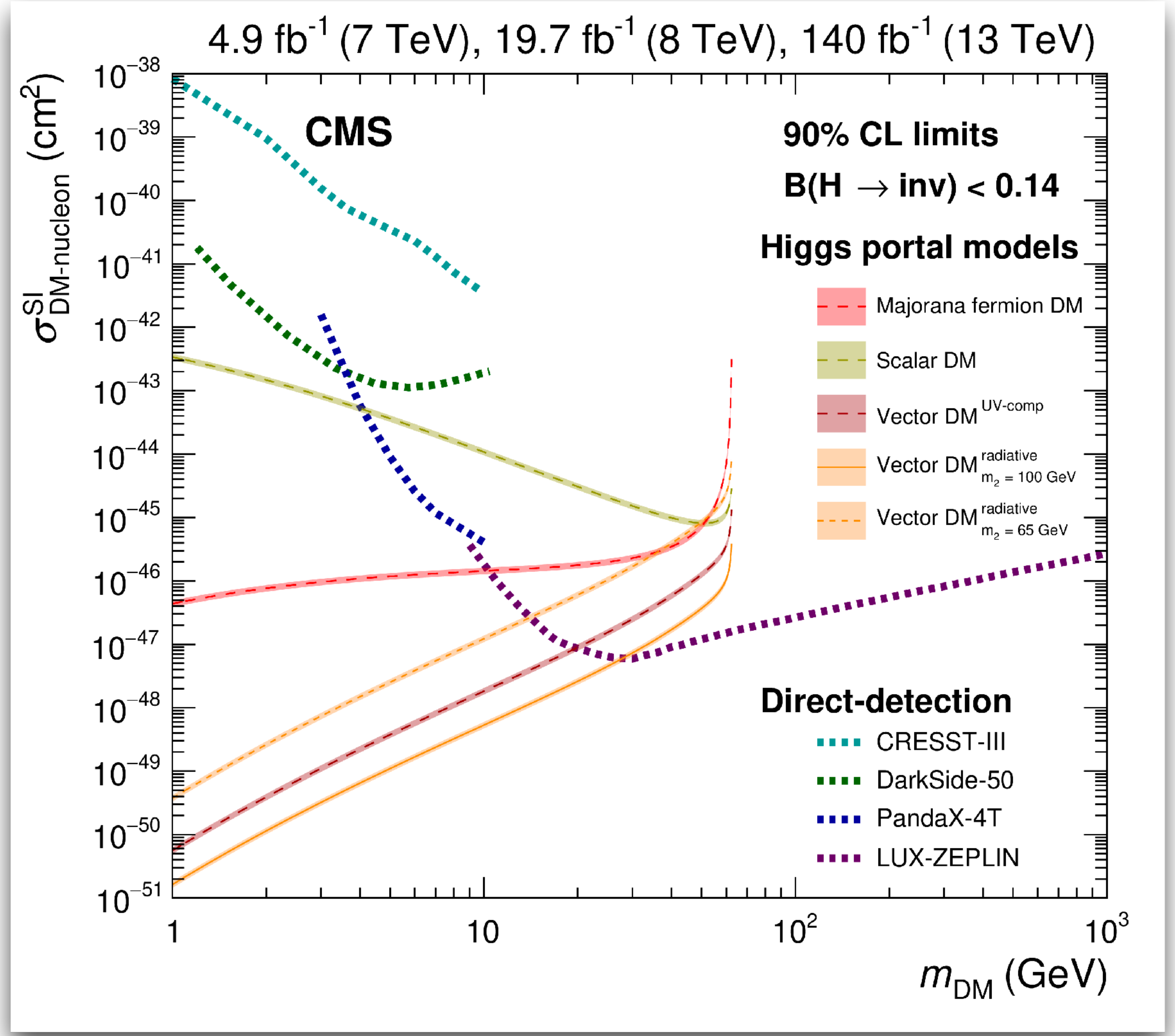
$H \to invisible$

- Direct searches with MET

ttH + VH $BR(H \to \text{inv.}) < 0.15\ (0.08)$ at 95% CL

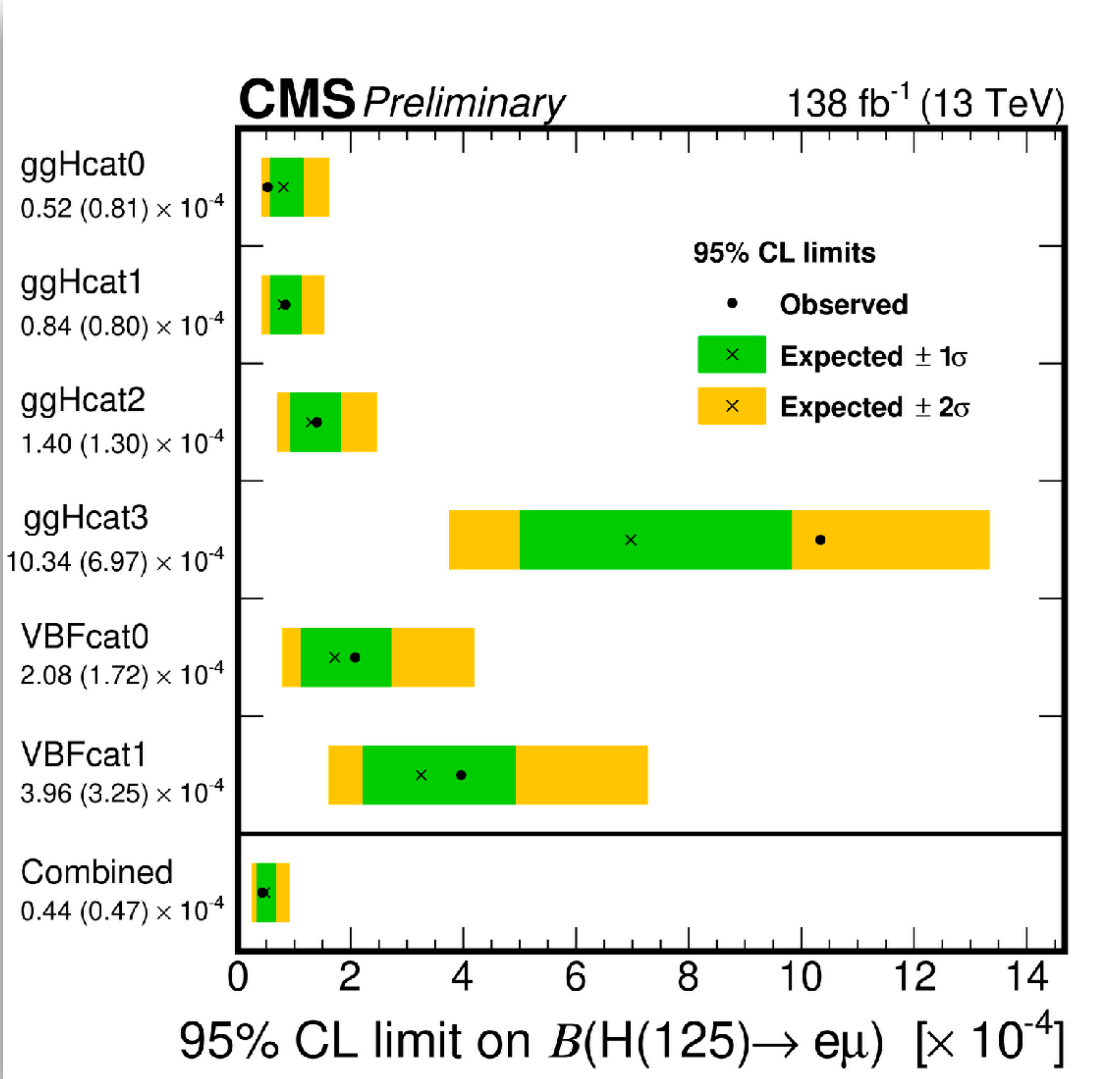
Submitted to EPJC

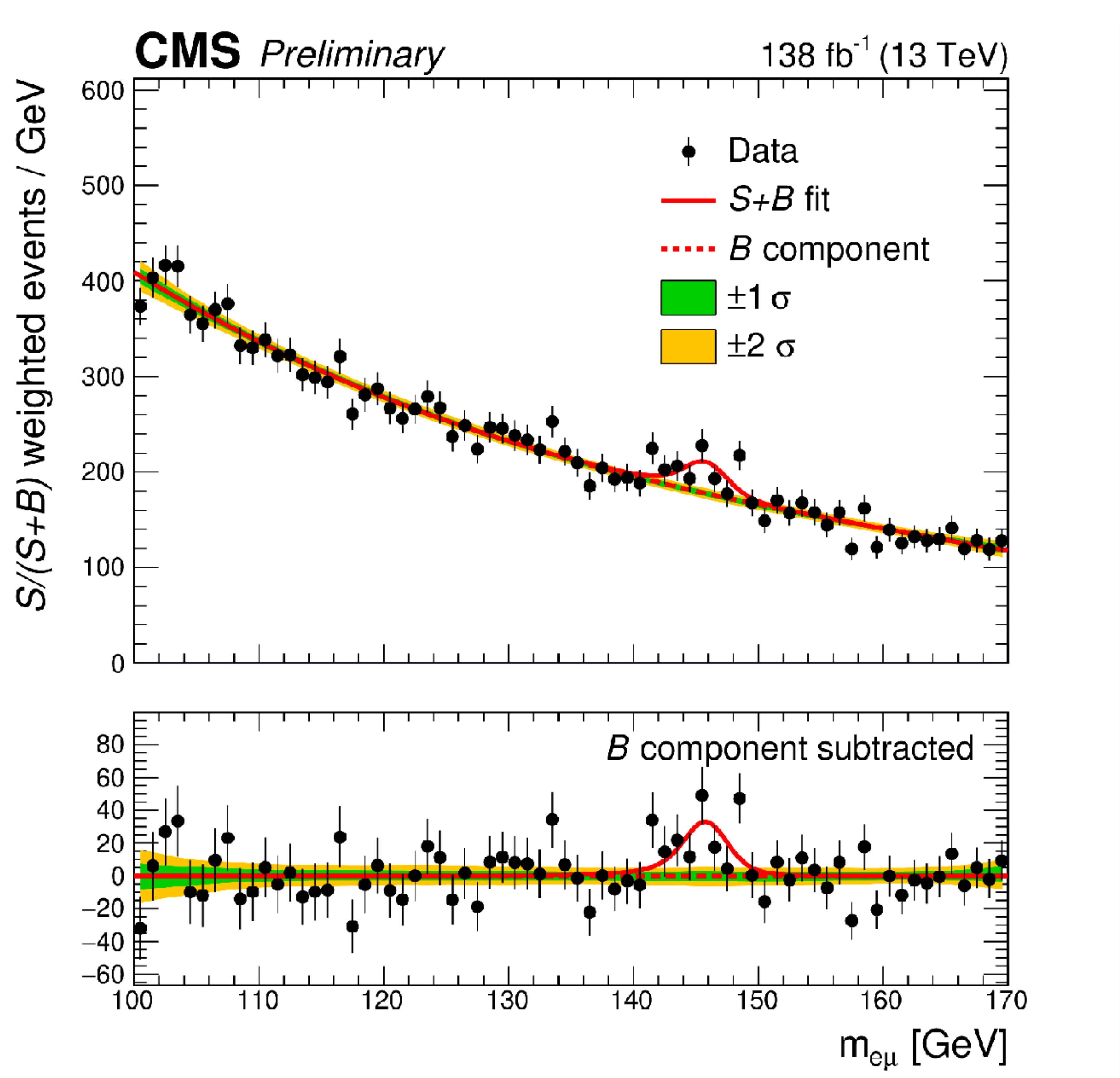


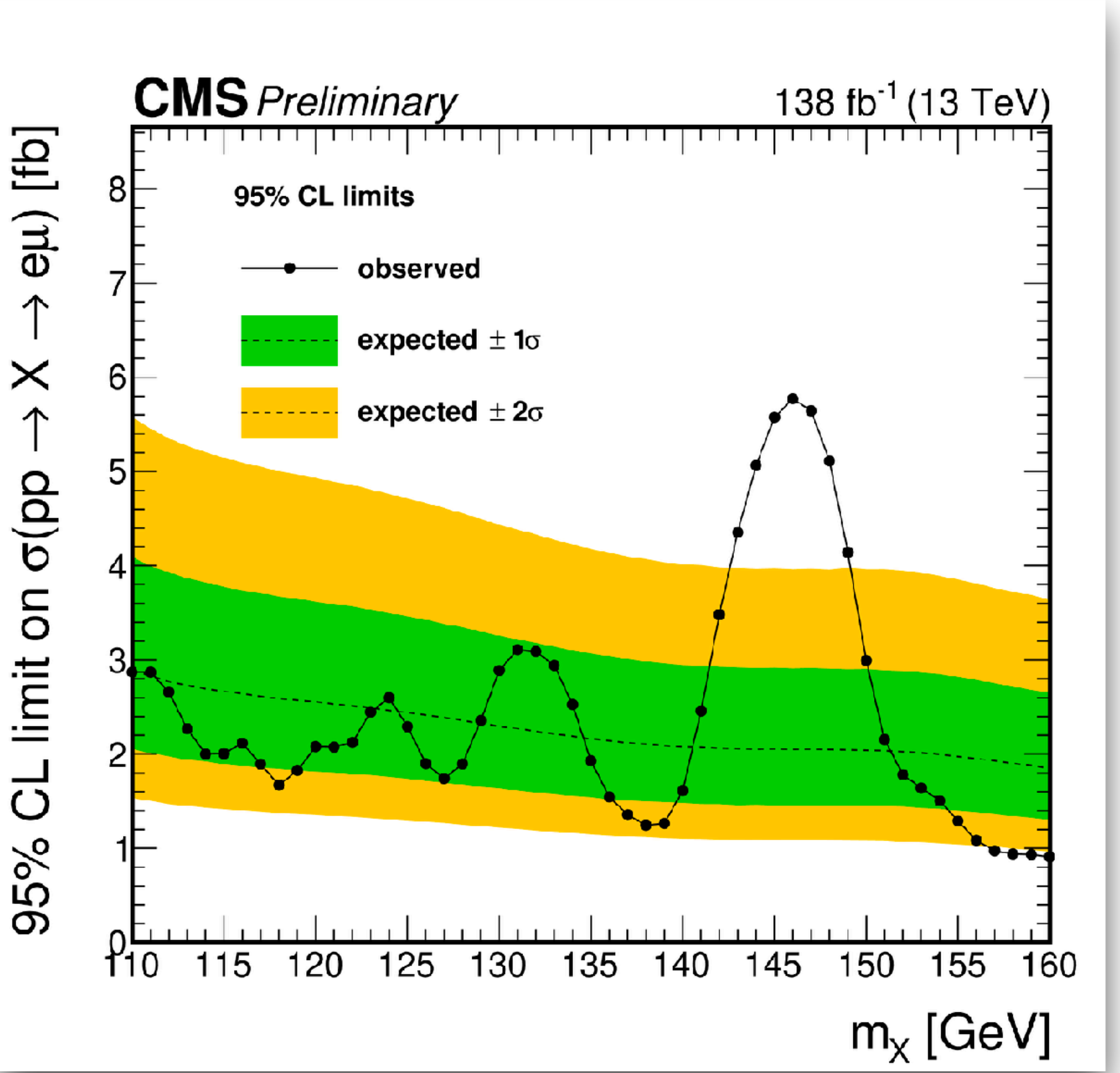


Higgs decays with lepton-flavor violation

- Scan for $H \to e\mu$ in the mass range of 110 to 160 GeV Submitted to PRD
- Categorize with BDT for ggH and VBF separately, fit on $m_{e\mu}$





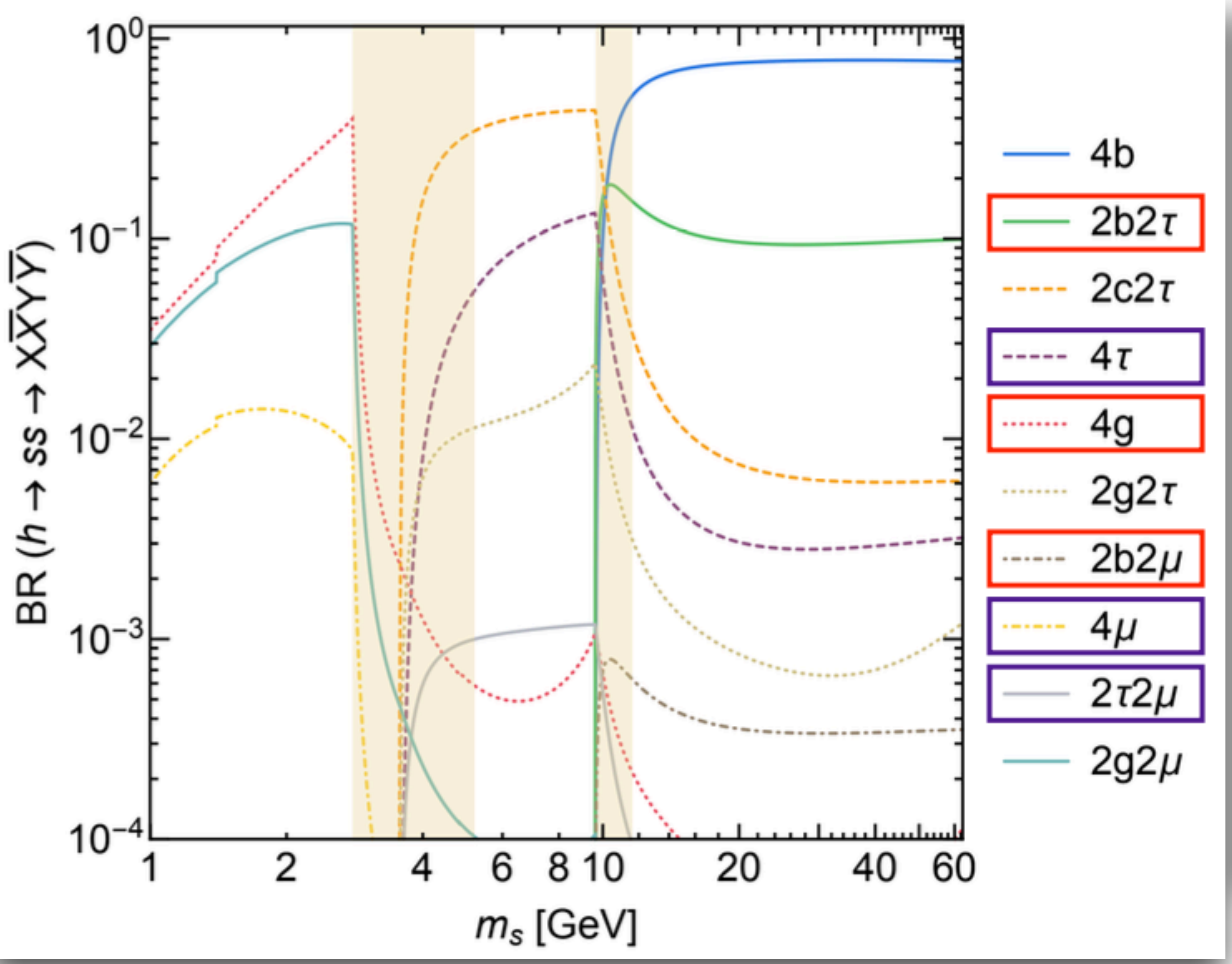


$BR(H \to e\mu) < 4.4\ (4.7) \times 10^{-5}$ at 95% CL

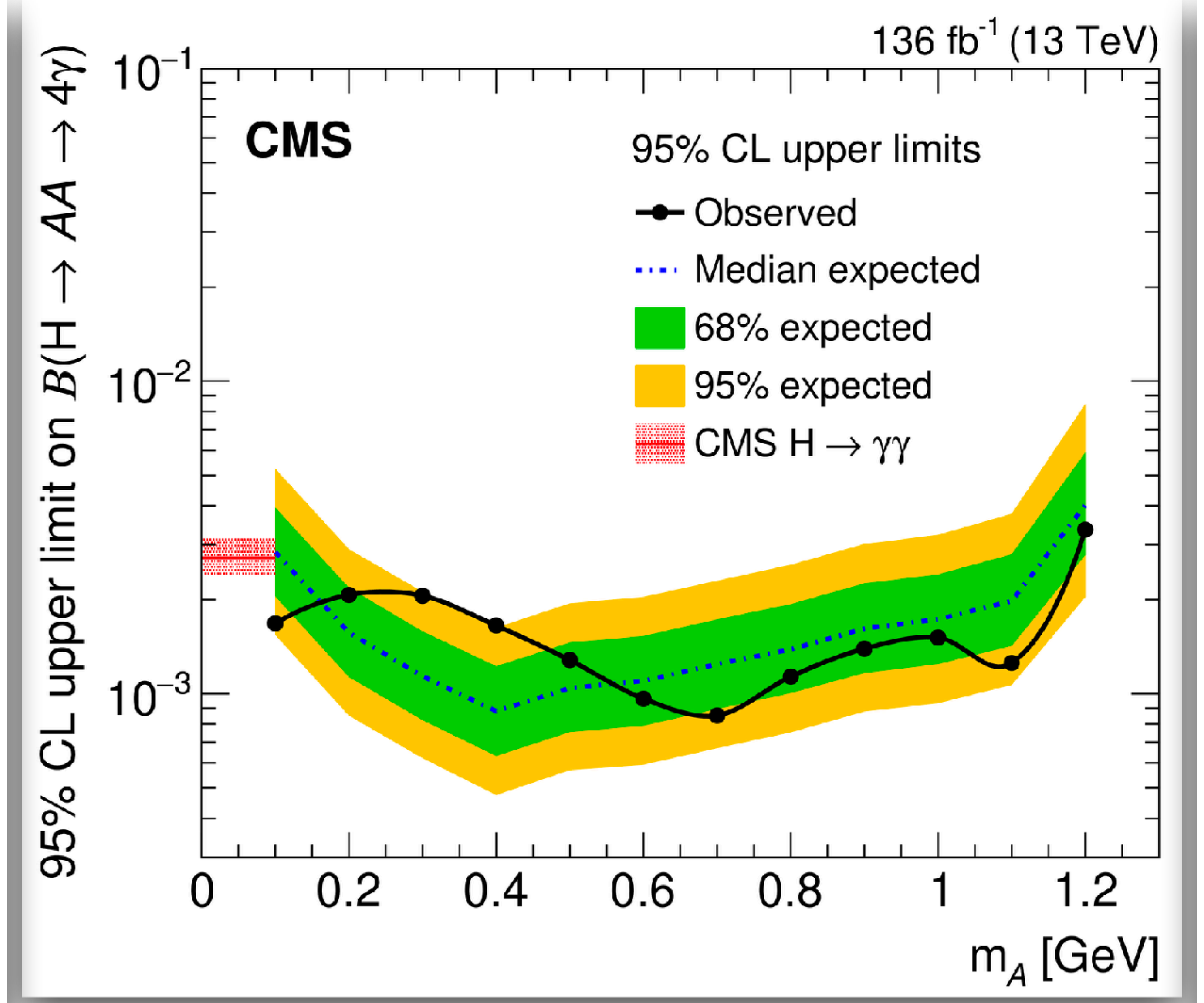
Found small excess of 3.8σ (2.8σ) local (global) at 146 GeV

Higgs to pseudoscalars

- Copious BSM scenarios (2HDM, 2HDM+S, singlet, NMSSM, axion etc.) expect Higgs to decay to a pair of pseudoscalars and are extensively searched at CMS



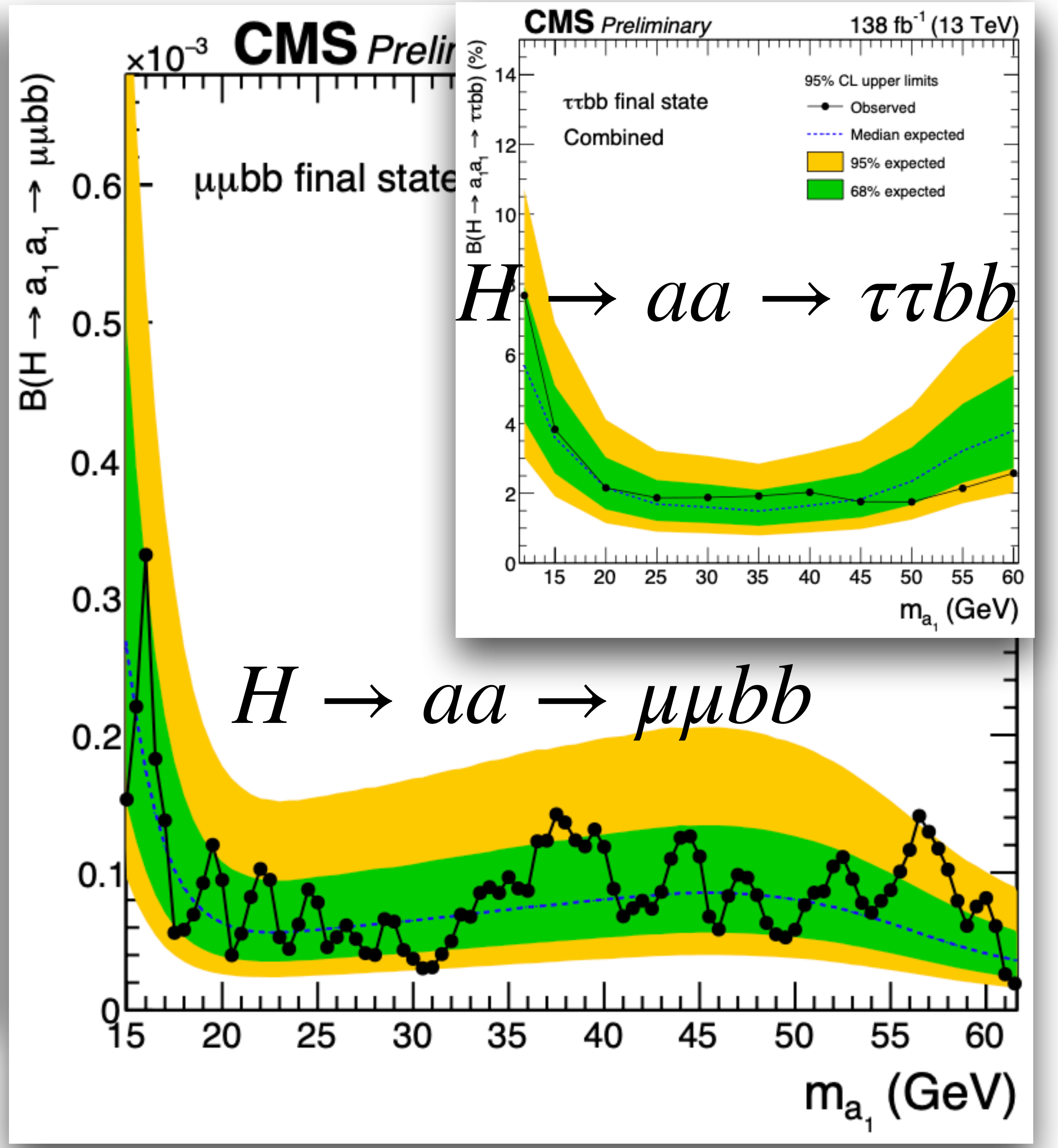
Channels sensitive in different mass ranges



$H \to aa \to 4\gamma$

First merged diphoton topology!

Accepted by PRL

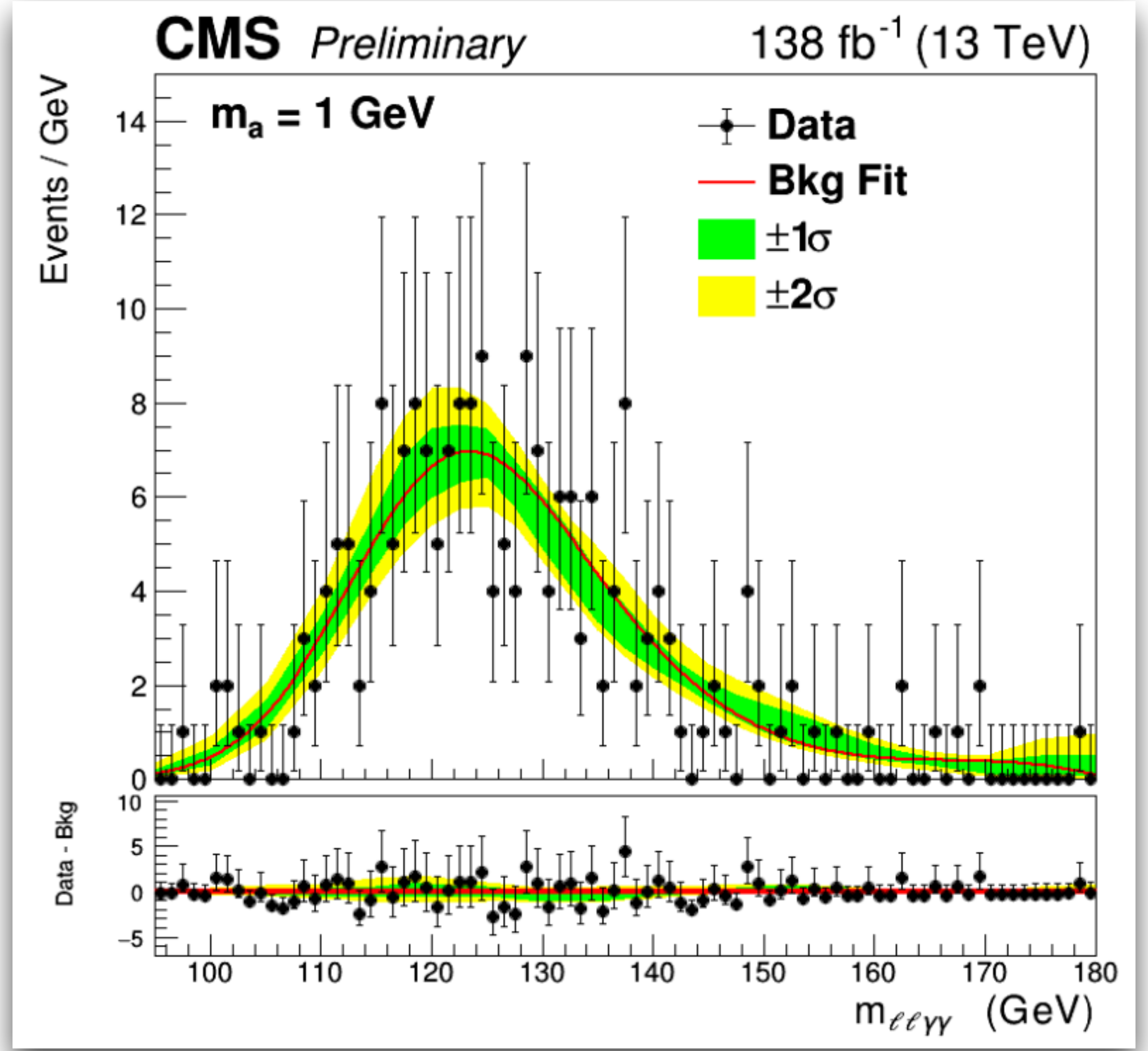


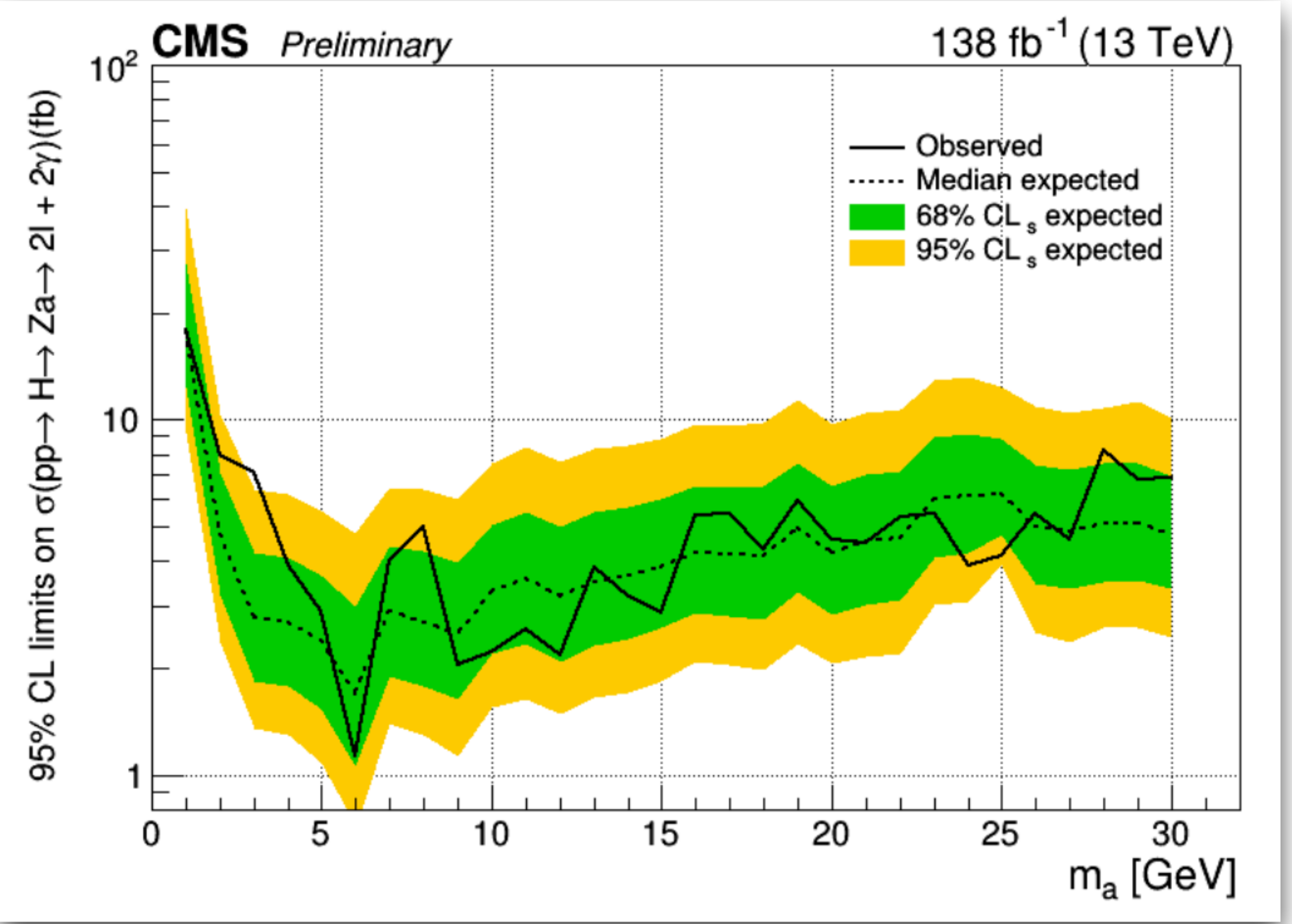
CMS-PAS-HIG-22-007

Higgs to pseudoscalars

- Instead of pairs, Higgs to Z+pseudoscalar is searched as well
- Unique signature with *llγγ* classified with a BDT

CMS-PAS-HIG-22-003





HH

- The double Higgs processes (HH) provides a direct probe to the Higgs self-coupling and the four-boson coupling VVHH κ_{2V}, but very challenging as its XS is 3 orders of magnitude smaller than the single Higgs
- The HH sensitivity already surpassed the single Higgs in terms of Higgs self-coupling
- Both HH production and decays have been explored extensively
  - Production: ggH, VBF and VHH
  - Decays: $4b$, $bb\tau\tau$, $bb\gamma\gamma$, $bbWW$, $bbZZ$, $\tau\tau WW$, 4τ, $4W$, $WW\gamma\gamma$

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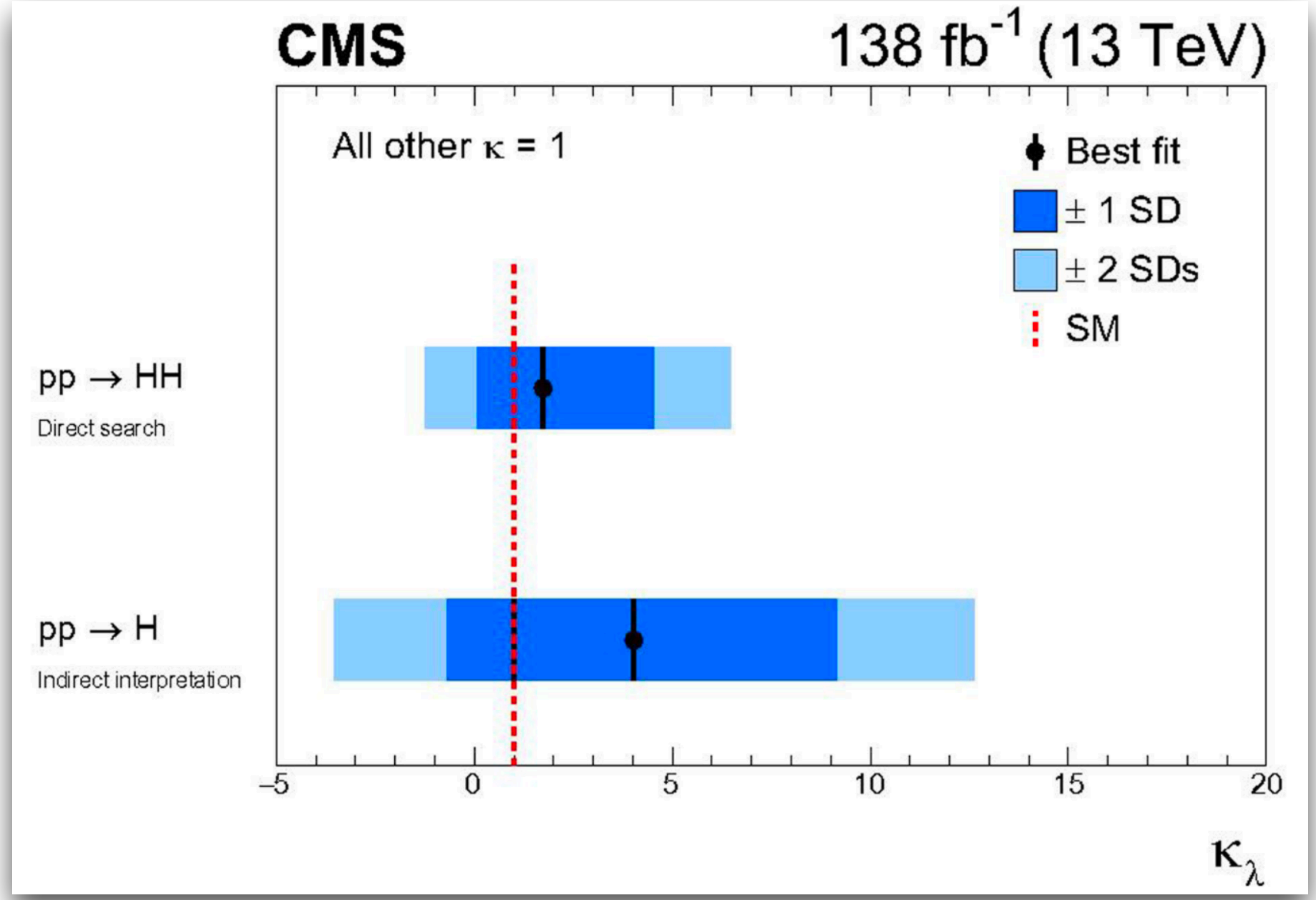
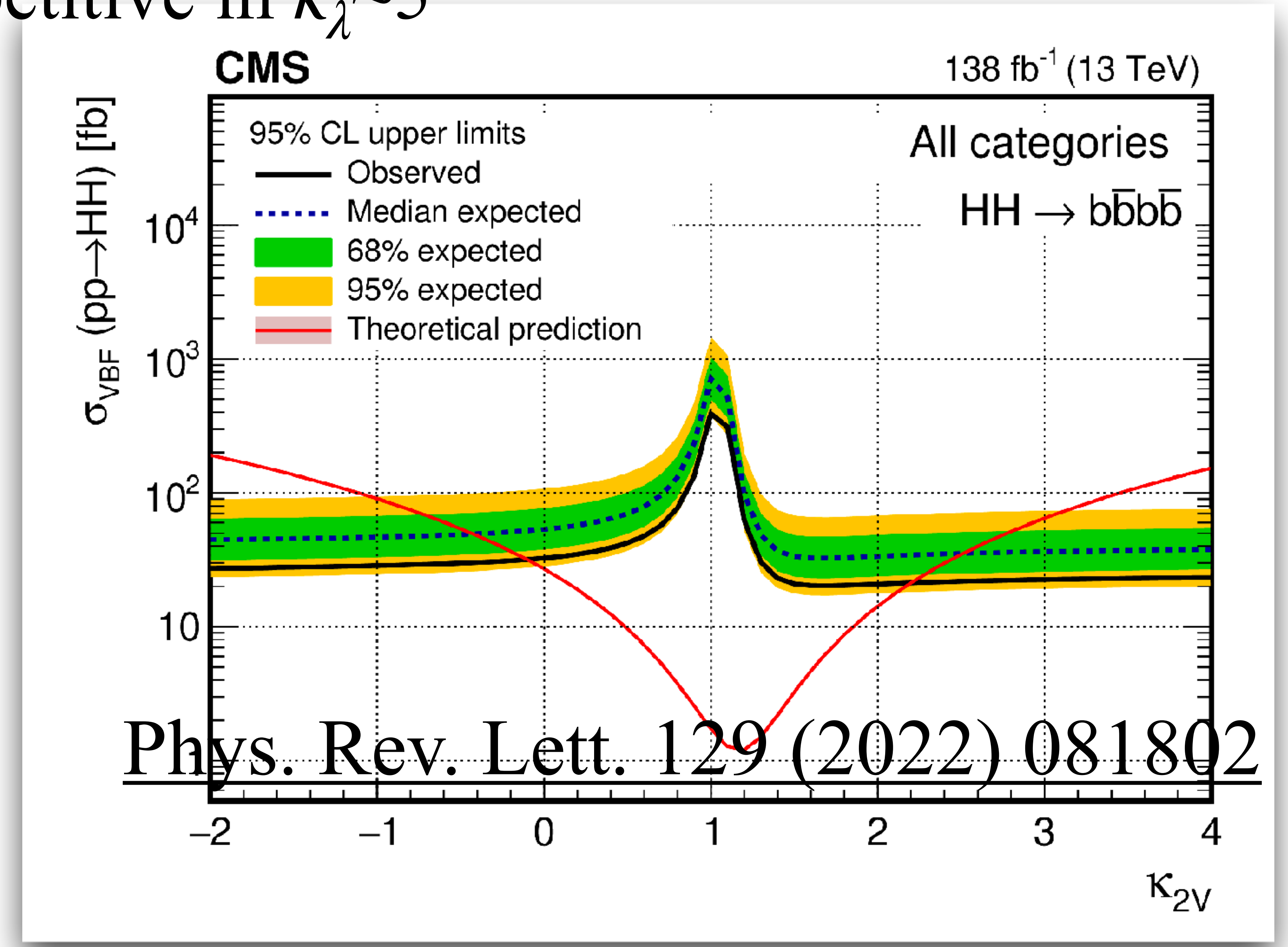
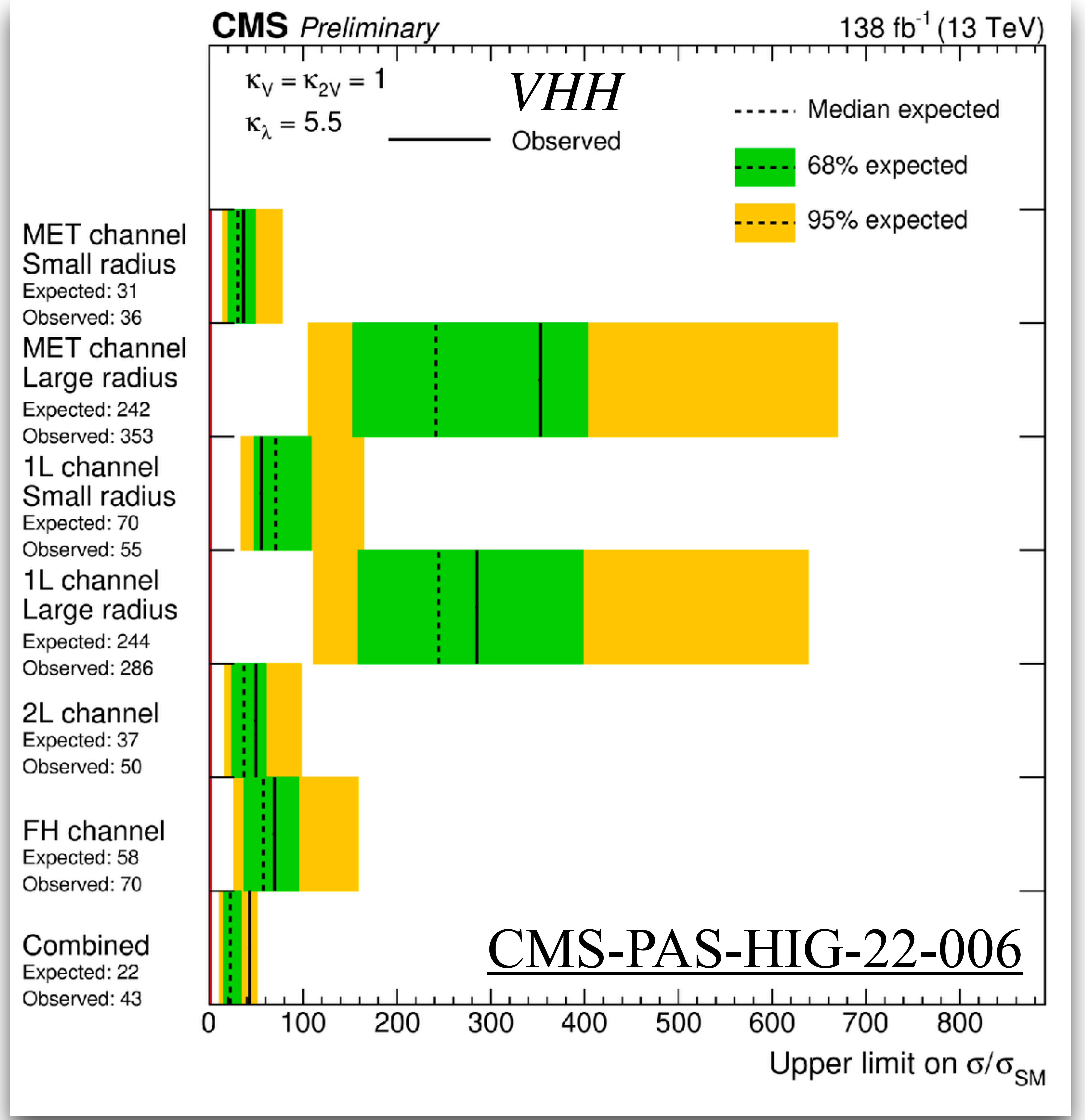


HH with 4b

- Stats deliver in HH thanks to its largest BR among all
- Measure HH XS with an upper limits of 3.9 (7.8)xSM
- The boosted 4b excludes $\kappa_{2V} = 0$ for more than 5σ
- The VHH is also probed using 4b and provide unique probes to WWHH and ZZHH separately, and can be competitive in κ_λ~5



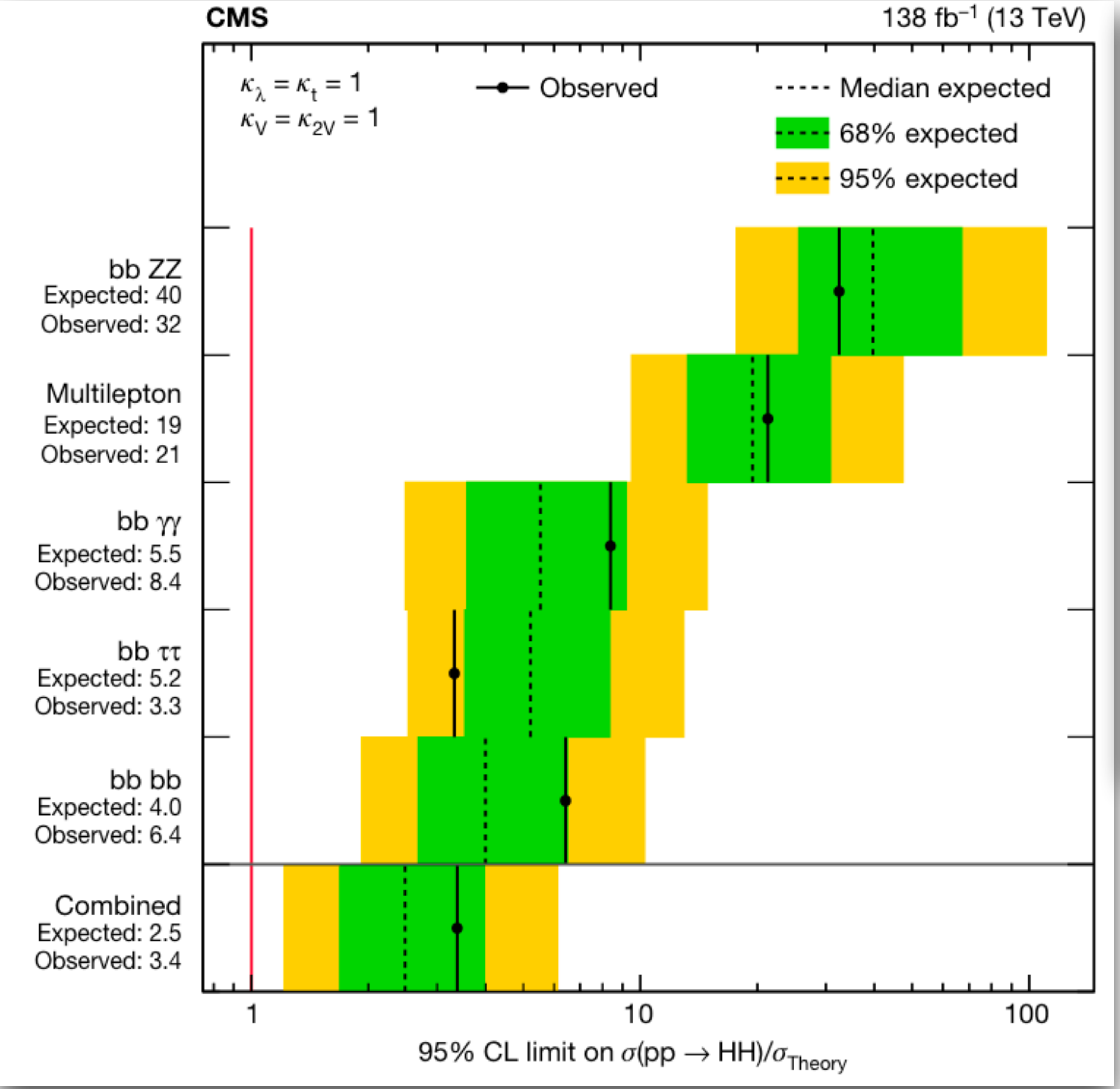
Phys. Rev. Lett. 129 (2022) 081802

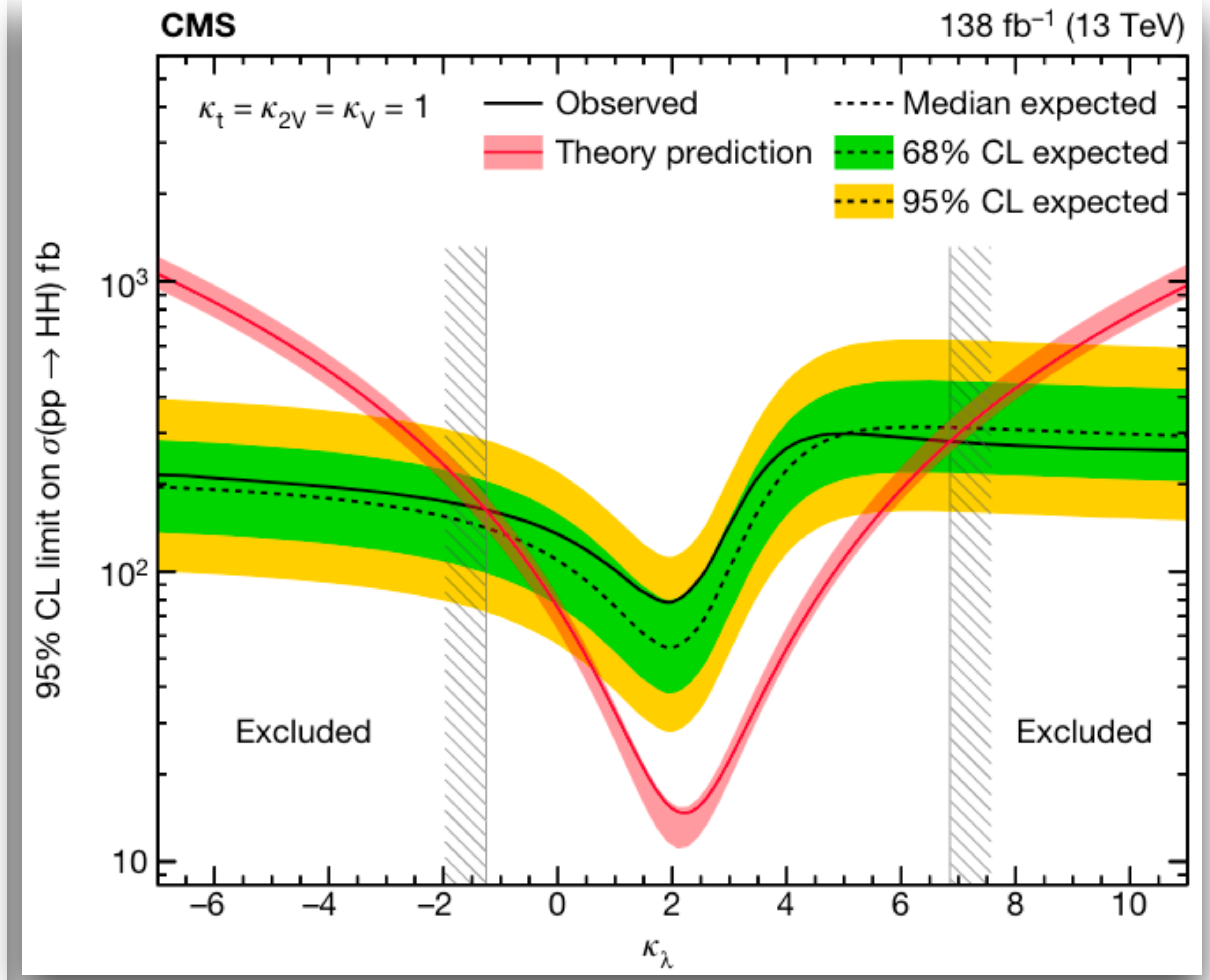


CMS-PAS-HIG-22-006

HH combined

- Still in the era of search, upper limits get more stringent
- The combined XS upper limit reaches 2-3 times of the SM prediction
- The constraint on κ_{2V} is impressive largely due to 4b boosted





$$-1.24 < \kappa_\lambda < 6.49$$

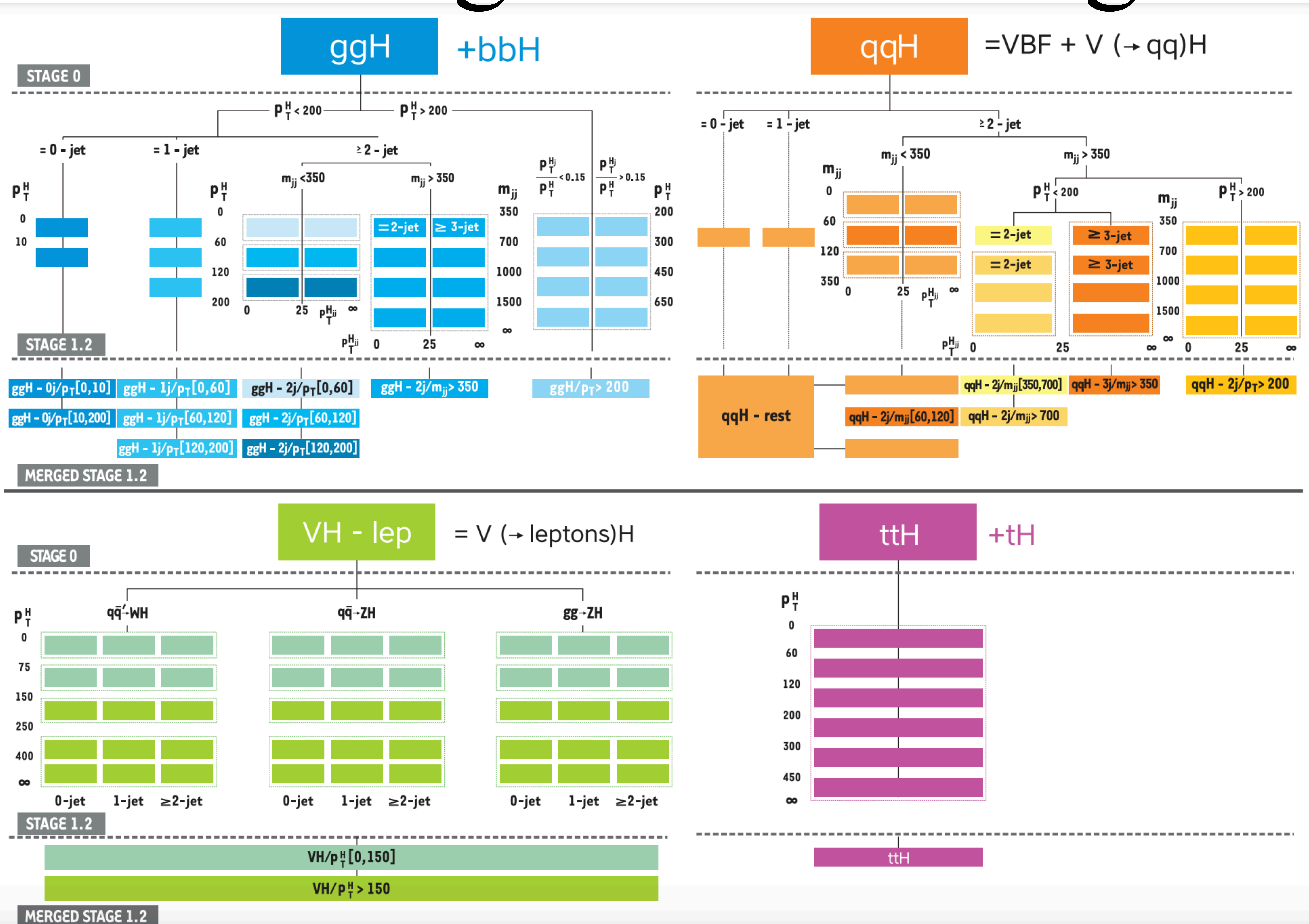
Nature 607 (2022) 60-68

Summary

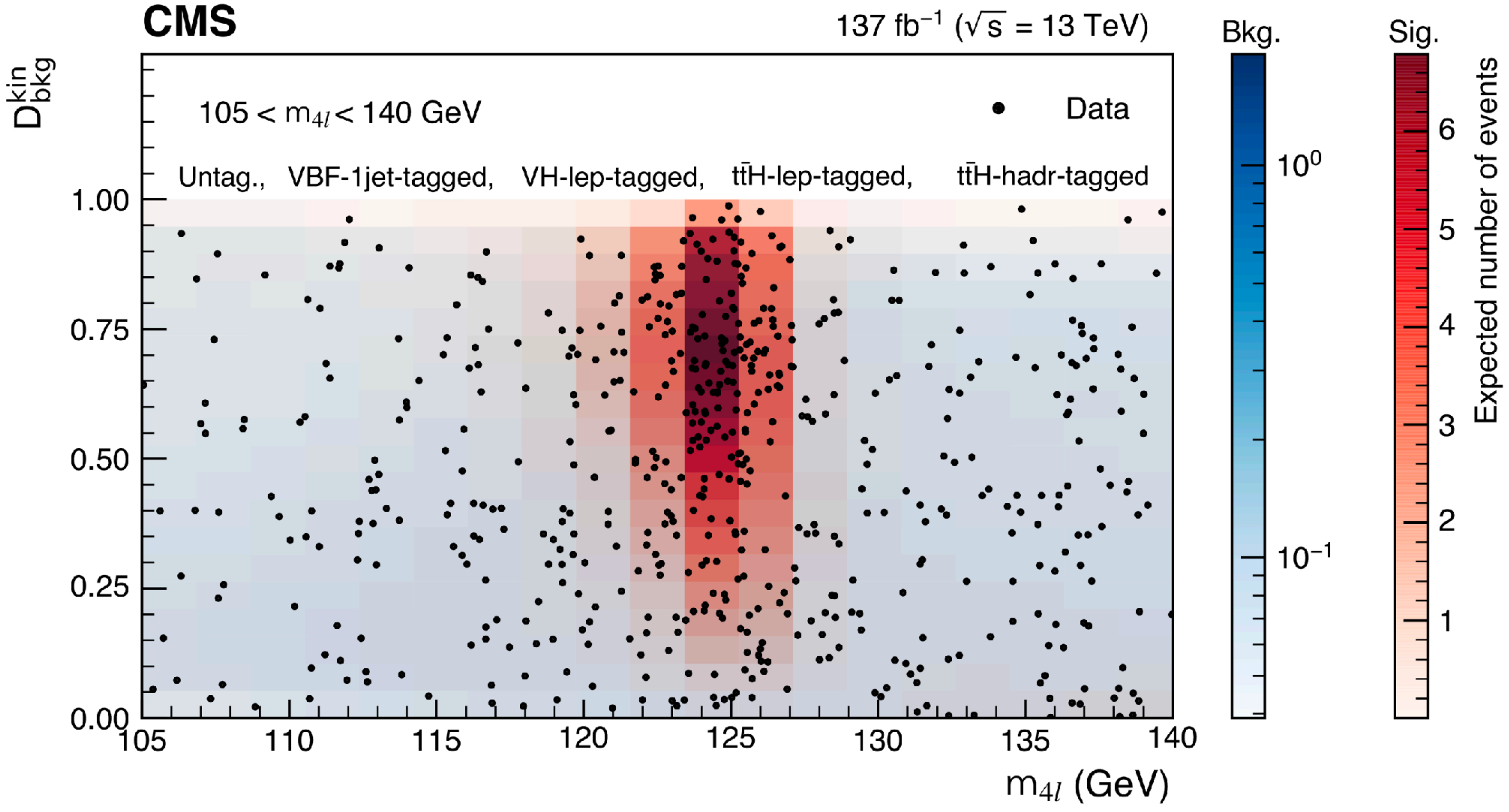
- It has been a decade after the discovery, and the profile of the Higgs boson becomes more clearer, but there are many unknowns
- STXS stage 1.2 precision can be as good as ~10%
- The Higgs mass is measured to the level 0.1%; The width is measured with the best precision ever using on/off-shell productions
- Higgs couplings are in general at 10% and reaching out to the 1st/2nd generation fermions
- HH keeps exploring and its upper limit is reaching ~2xSM
- Higgs pair searches excluded $\kappa_{2V} = 0$
- No obvious sign of anomalous couplings yet

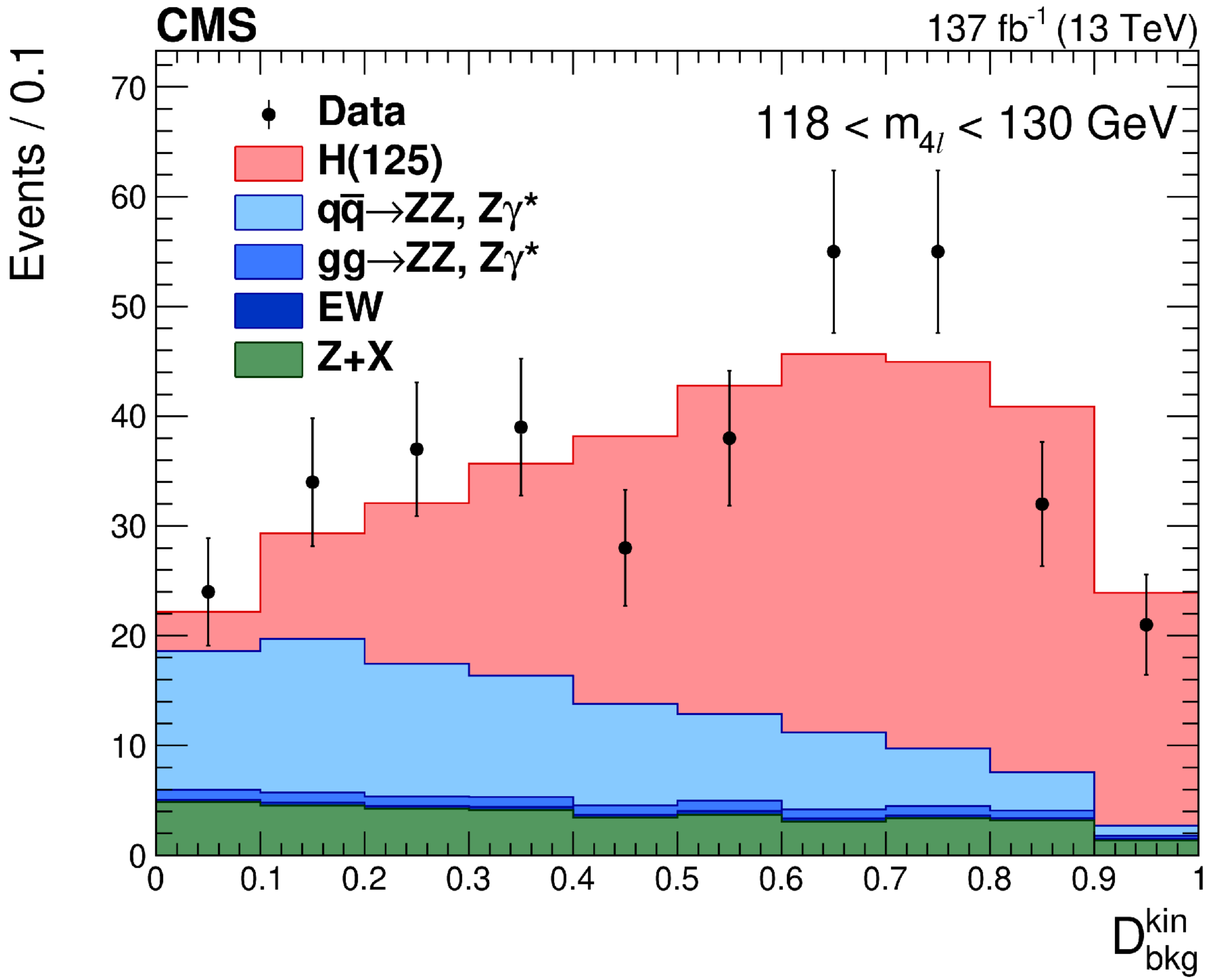
Backup

HZZ4l merged STXS Stage 1.2

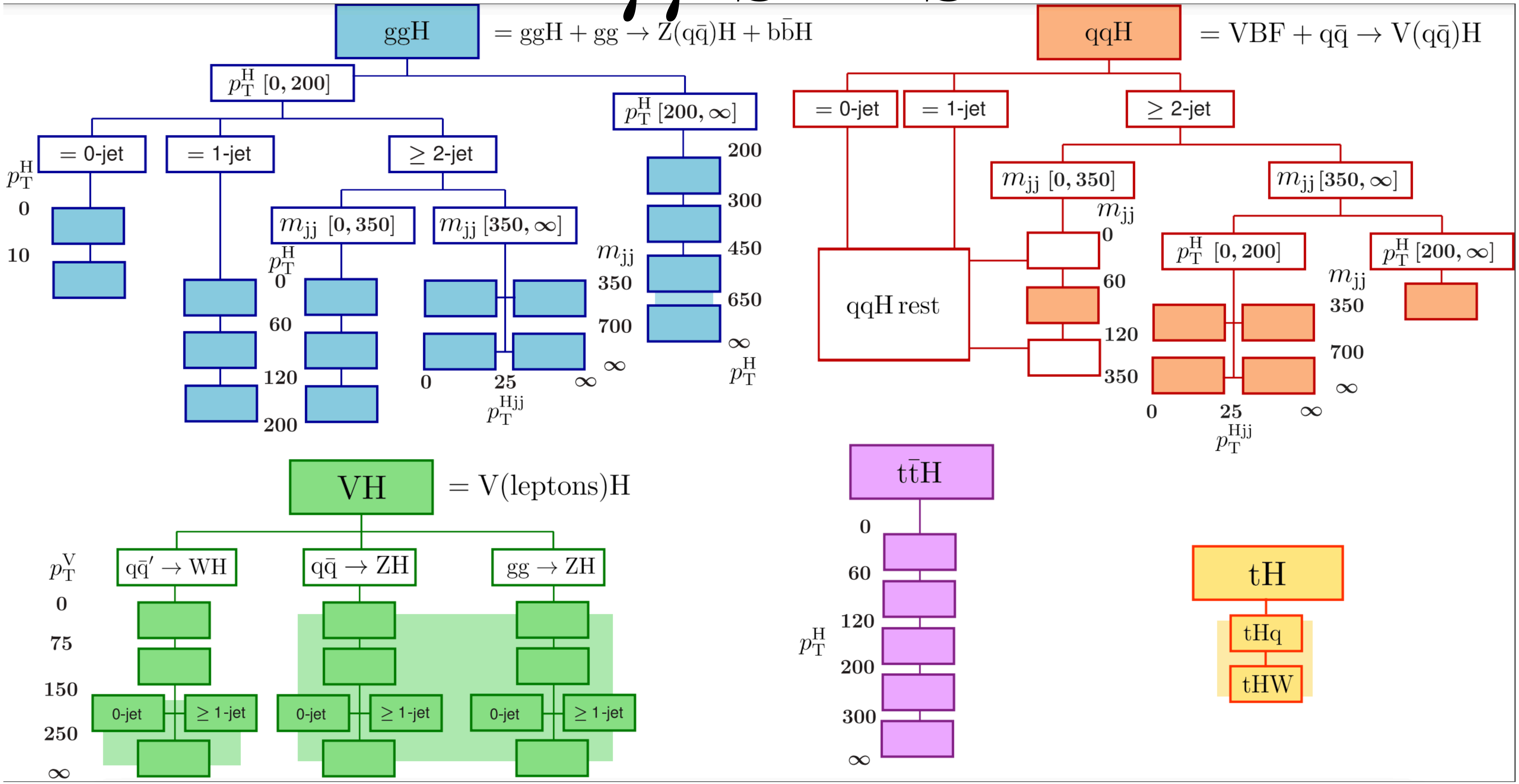


HZZ4l


CMS
137 fb⁻¹ (√s = 13 TeV)
105 < m4l < 140 GeV
Data
Untag., VBF-1jet-tagged, VH-lep-tagged, tt̄H-lep-tagged, tt̄H-hadr-tagged
D^kin_bkg
m4l (GeV)
Bkg.
Sig.
Expected number of events

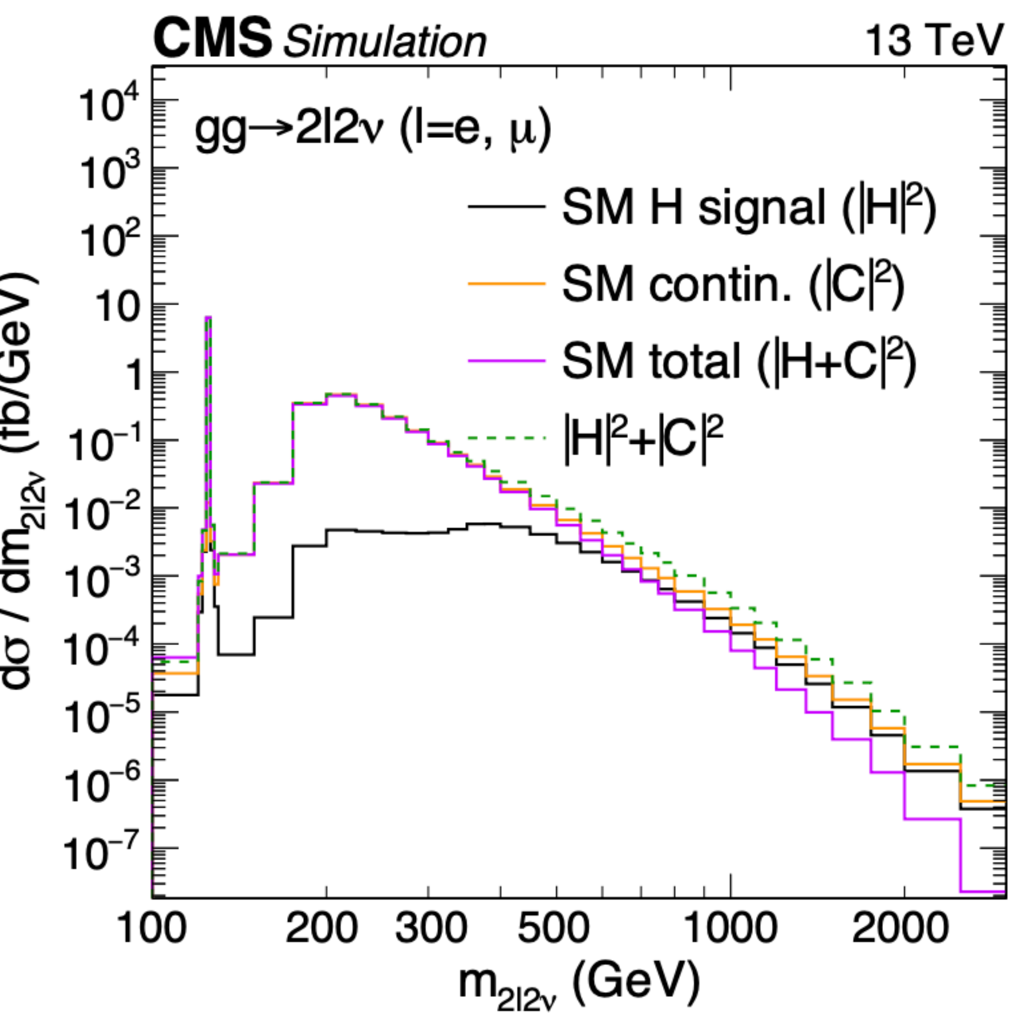

CMS
137 fb-1 (13 TeV)
118 < m4l < 130 GeV
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
EW
Z+X
Events / 0.1
D^kin_bkg

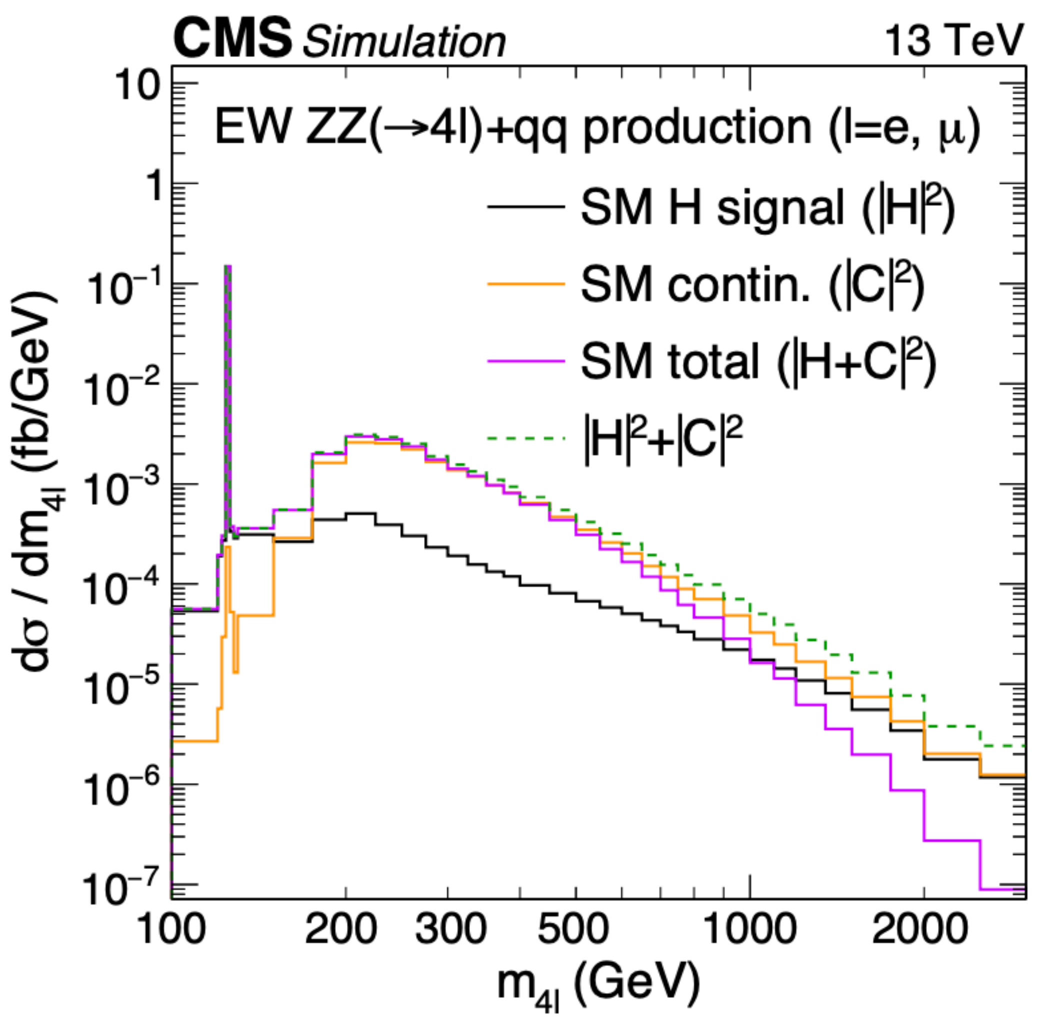
$H\gamma\gamma$ STXS

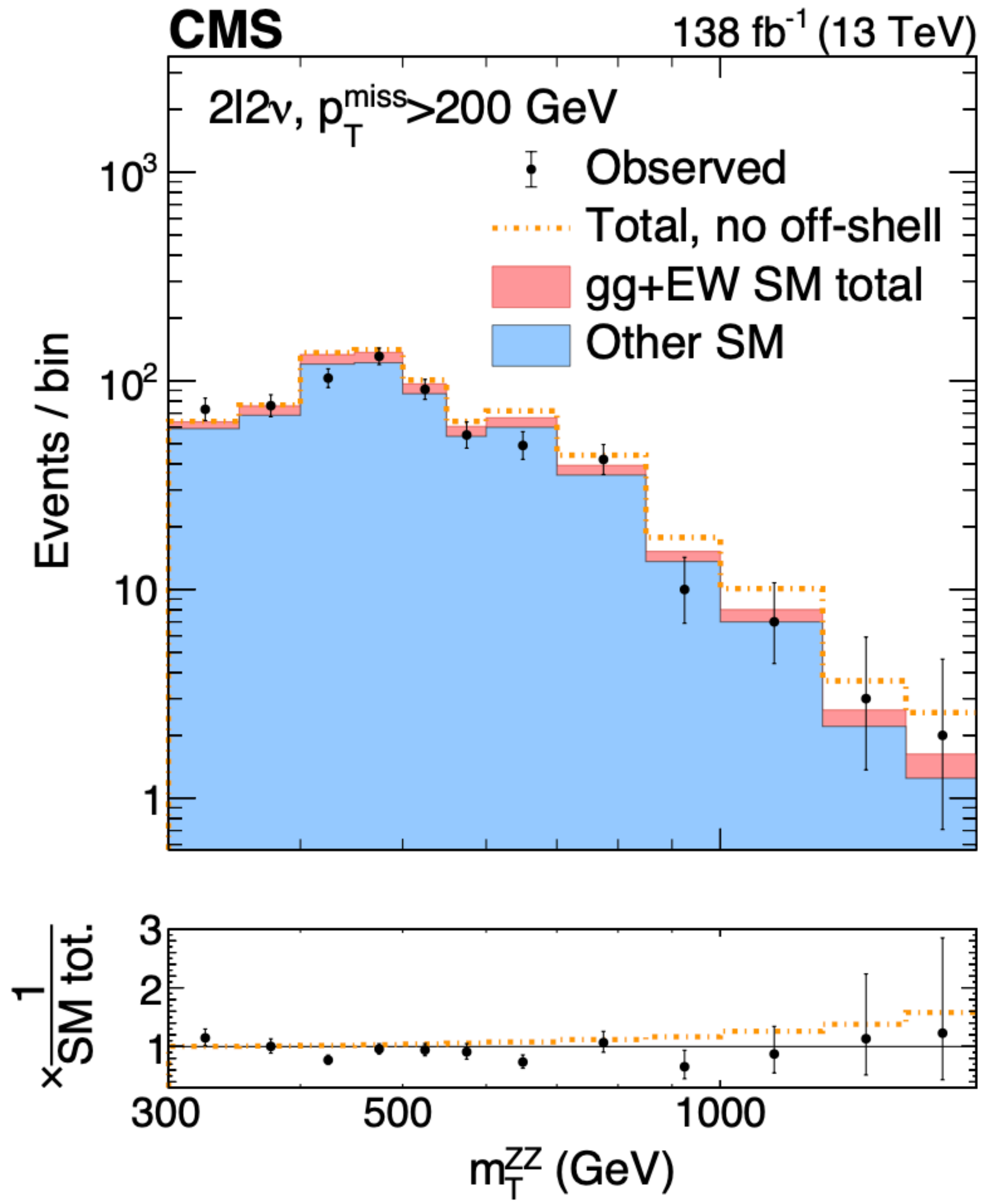


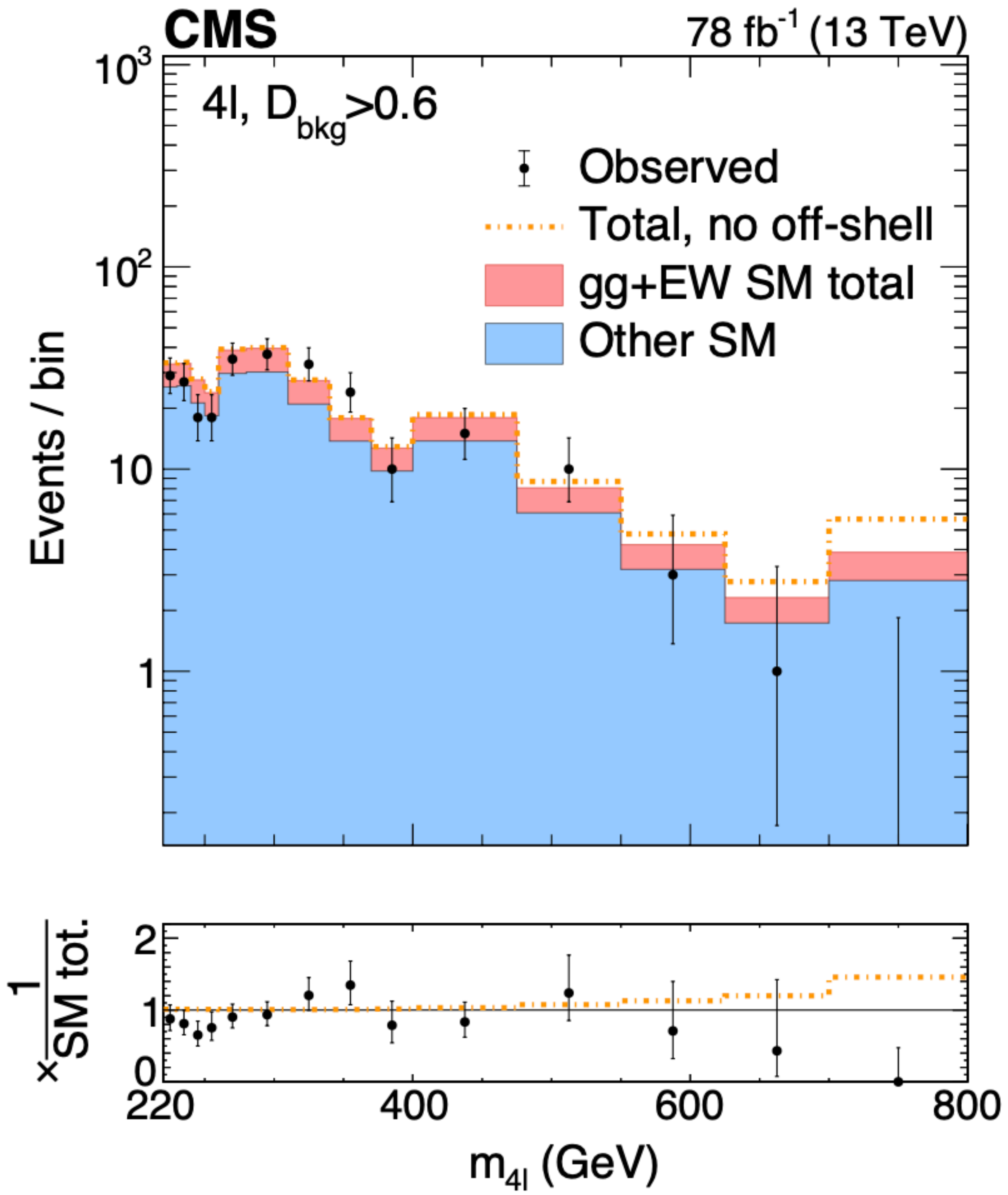
The shaded regions indicate the STXS bins that are divided at stage 1.2, but are not measured independently in this analysis.

The width









4l takes its advantage in on-shell

llvv plays an important role in off-shell

The stacked histogram displays the distribution after a fit to the data with SM couplings, with the blue filled area corresponding to the SM processes that do not include H boson interactions, and the pink filled area adding processes that include H boson and interference contributions

Higgs AC and EFT

Direct analysis following the **anomalous couplings (AC)** parametrization
→ target ggH and VBS Higgs productions

Limits on AC parameters can be rotated to Warsaw basis WC limits.

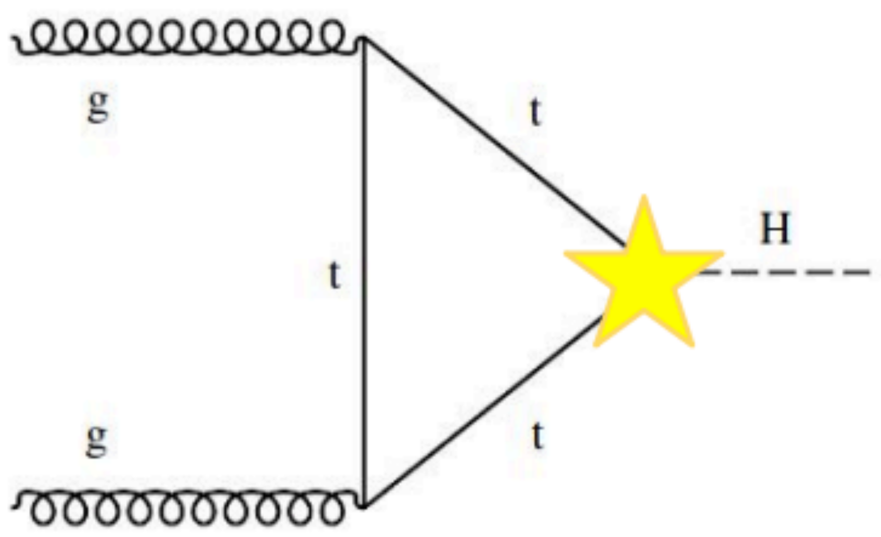
AC approach/SMEFT approach
1 Anomalous coupling:
$\tilde{\kappa}_f$: ~~CP~~

AC approach	SMEFT approach
$a_i^{ZZ}=a_i^{WW}$	SU(2) X U(1)
4 anomalous couplings:	$a_i^{ZZ} \neq a_i^{WW}$
a_2 (CP)	3 anomalous couplings:
a_3 (~~CP~~)	a_2 (CP)
$a_{\Lambda 1}$ (CP)	a_3 (~~CP~~)
$a_{\Lambda 1}^{Z\gamma}$ (CP)	$a_{\Lambda 1}$ (CP)

$$A(\mathrm{Hff}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + i\,\tilde{\kappa}_f\gamma_5\right)\psi_f\,,$$

CP-even

CP-odd

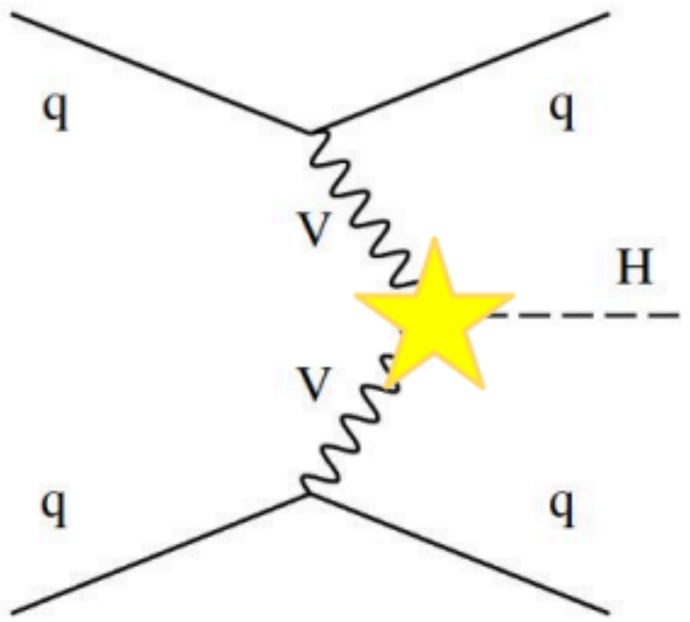


$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}\left(q_{V1}+q_{V2}\right)^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\,,$$

SM

CP-even

CP-odd



$$f_{CP}^{\mathrm{Hff}} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$

Observables:
XS fractions

$$f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_{j=1,2,3...}|a_j|^2\sigma_j}\,\mathrm{sign}\left(\frac{a_i}{a_1}\right)$$

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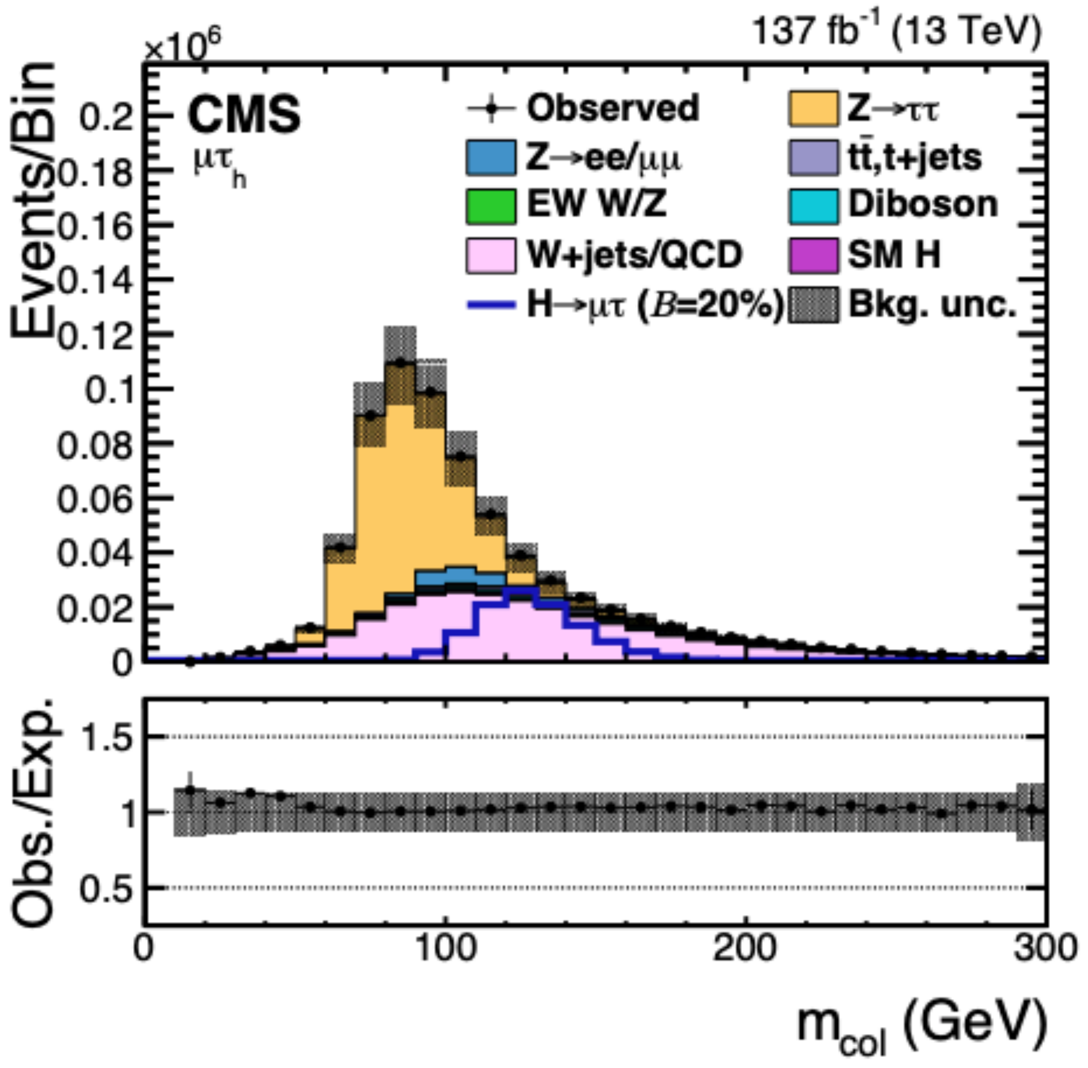
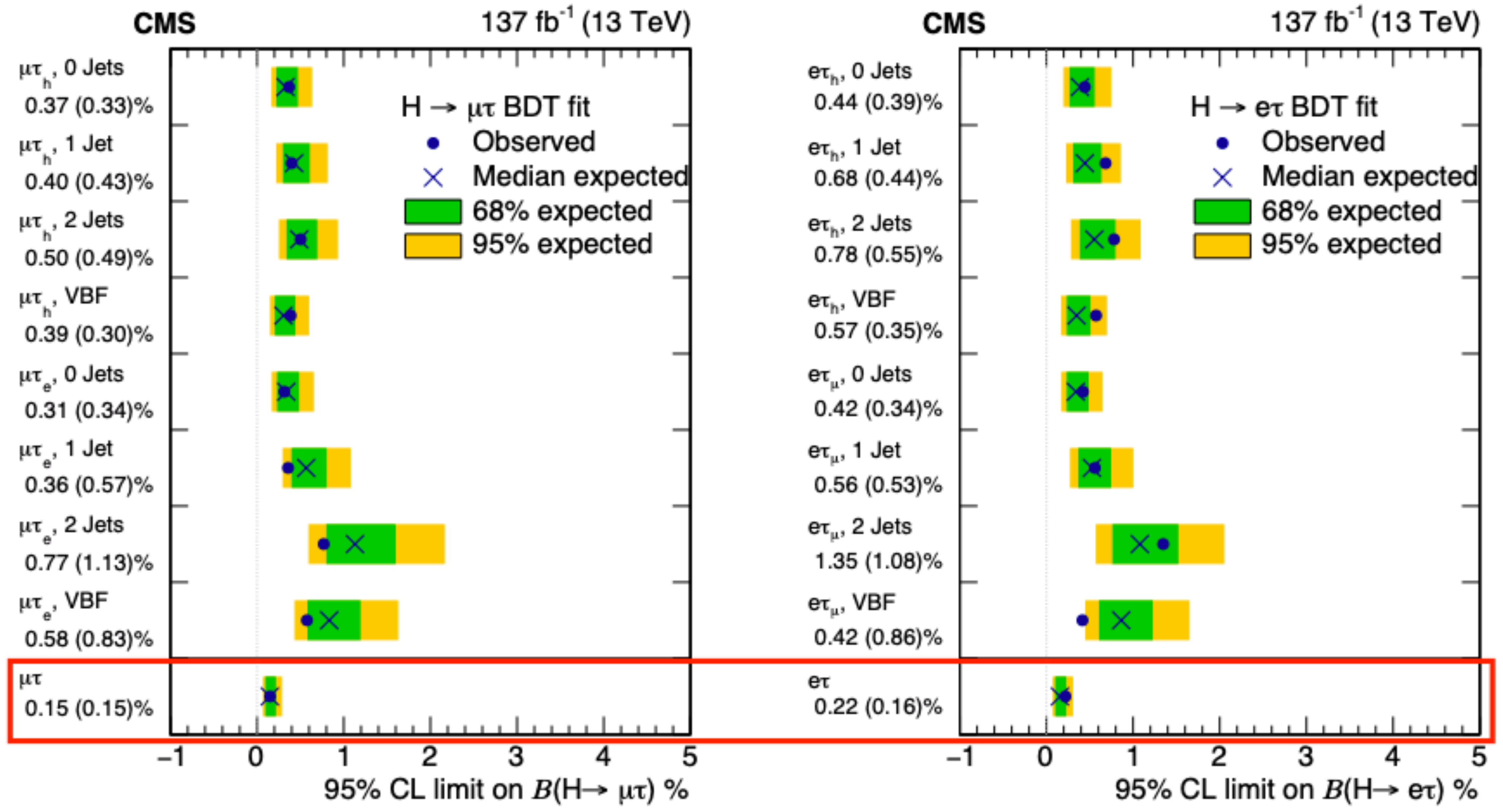
$H \to e\tau, \mu\tau$

Overview:

- Multiple signal region categories based on τ decay and jet multiplicity to enhance sensitivity
- Construct collinear mass variable $m_{col} = m_{vis}/\sqrt{x_\tau^{vis}}$ to estimate m_H

A BDT is trained in each channel and the discriminant distribution is used in a maximum likelihood fit to extract the upper limits on the Higgs BR





Analysis constrains BR(H→μτ) < 0.15 and BR(H→eτ) < 0.16 at 95% CL

Also provides upper limits on LFV Yukawa couplings: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.11 \times 10^{-3}$ and $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$

Phys. Rev. D 104 (2021) 032013

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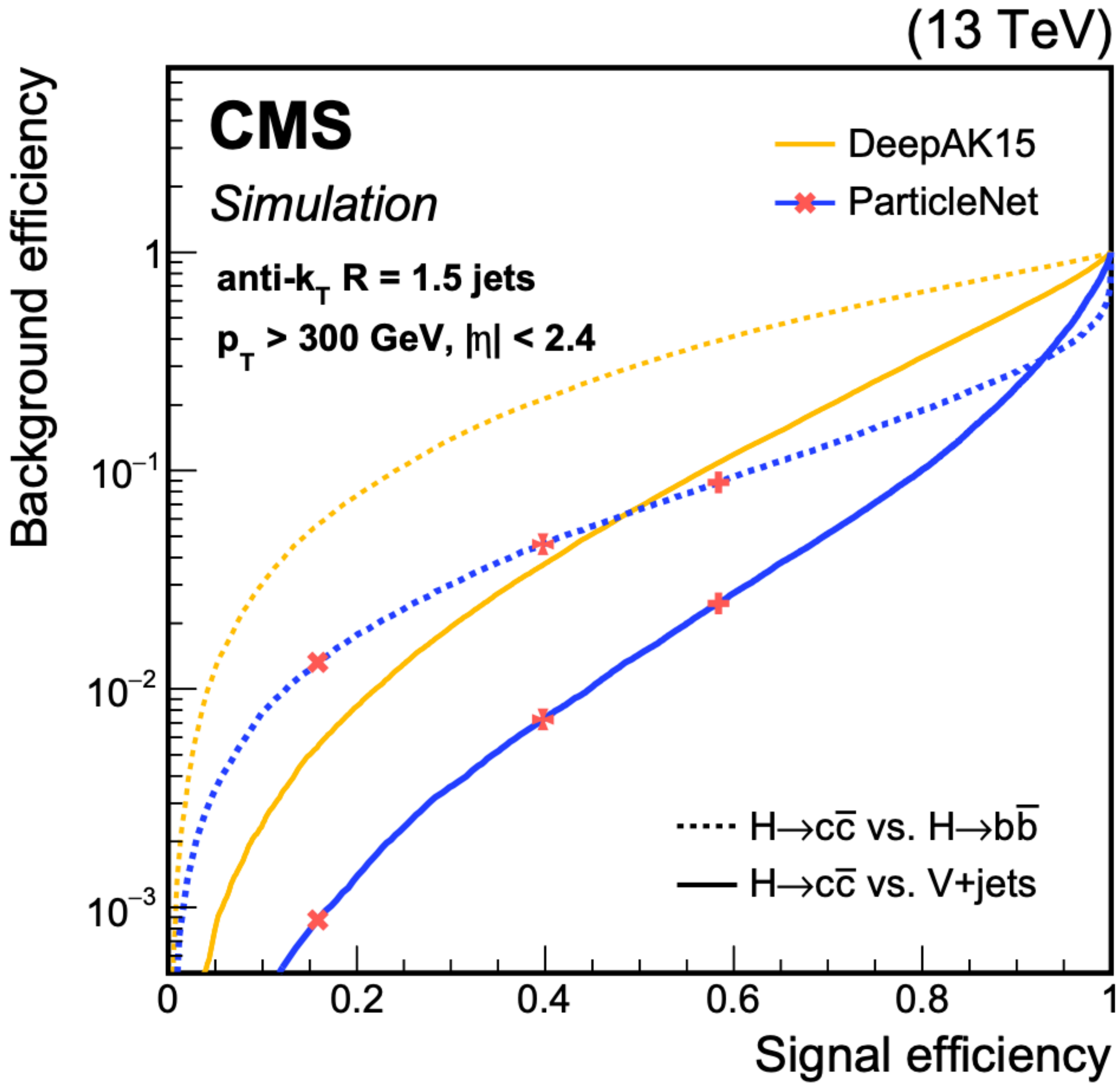
Hcc


(13 TeV)
CMS
Simulation
anti-k_T R = 1.5 jets
p_T > 300 GeV, |η| < 2.4
DeepAK15
ParticleNet
H→cc̄ vs. H→bb̄
H→cc̄ vs. V+jets
Background efficiency
Signal efficiency
1
10^{-1}
10^{-2}
10^{-3}
0
0.2
0.4
0.6
0.8
1